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THE ESTIMATION OF RUNOFF FROM SMALL RURAL CATCHMENTS

by

J. R. Jones

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The University of New South Wales
School of Civil Engineering

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PREFACE

This report forms the basis of a thesis submitted by Mr. J. R. Jones for the degree of Master of Engineering in the School of Civil Engineering of The University of New South Wales and supervised by Professor E. N. Laurenson. The study is part of a continuing programme in the Hydrology Section of the School of Civil Engineering on the development of mathematical models of the rainfall-runoff process.

The work was carried out under a grant from the Rural Credits Development Fund of the Reserve Bank of Australia, and this help is gratefully acknowledged.

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SYNOPSIS

The Boughton daily rainfall-runoff model was simplified to contain four parameters directly related to physical catchment characteristics. Procedures were determined for estimating the parameter values and then tested by application to the data of an independent catchment. The results of the test are discussed and suggestions proposed for future research.

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1. INTRODUCTION

Literature surveys were made of the available methods for estimating yield and peak flow on small rural catchments in Australia. This work is detailed in two papers by Laurenson and Jones entitled "Yield Estimation for Small Rural Catchments in Australia" (1968) and "Flood Estimation for Small Rural Catchments in Australia" (1967).

It was decided that the research project should pursue the subject of yield, or total runoff, estimation. The review indicated that the daily rainfall-runoff model of W. C. Boughton (1965) presented the most promising method for development for estimating yield on ungauged catchments. It was therefore resolved to undertake the development of the model so that it could be used as a practical design procedure. This would involve the collation and evaluation of data to enable the parameters to be estimated on ungauged catchments and possible simplification of the model.

Research involving the Boughton model would also contribute to flood estimation research, for the model can be used to calculate catchment wetness and indicate the losses for a storm. The type of storm (high intensity with short duration or low intensity with long duration) and the corresponding catchment condition (saturated, moist or dry) which cause major floods are still the subject of investigation, Pilgrim (1966). If daily rainfall records are available for a catchment then the model may be used to determine the combinations of catchment condition and storm type which produced large floods.

2. BOUGHTON MODEL AND SUMMARY OF RESEARCH

This section commences with a description of the Boughton model, its operation and the parameters which need to be evaluated for its application to a catchment. The validity of the model, with respect to its modelling of the soil profile structure on actual catchments, is then discussed.

The section is concluded with a summary of the approach adopted and the work undertaken for this research project.

2.1 Description of the Boughton model

Boughton developed a model which visualizes a catchment as having two soil layers, a very porous topsoil layer above a denser subsoil. The model is illustrated in Fig. 1 and comprises four moisture stores, which are replenished by rainfall and diminished by evaporation and infiltration, with the balance being runoff.

The stores are:-

interception store
upper soil store
drainage store
lower soil store.

The interception store represents the film of moisture held on the surface of vegetation. Upon the commencement of rainfall, this store is filled to capacity and then overflows into the upper soil store. The interception store is depleted, until empty, by evaporation at the daily potential rate.

The upper soil store represents the moisture held in the topsoil layer which is available for transpiration by vegetation. Its capacity is equal to the product of the topsoil depth and the available water capacity (AWC) of the soil. (The AWC is the amount of moisture which the soil can retain in its capillary pores for use by plants, expressed as ins/ft depth of soil). Rainfall must fill this store before water can enter the drainage store. Evaporation first empties the interception store and then commences from the upper soil store. The depletion is at a rate proportional to the amount of moisture in the store, or at the potential rate, whichever is the lower.

The drainage store is replenished by overflow from the upper soil store. It represents the moisture temporarily held in the non-capillary pores of the upper soil and which later infiltrates to the lower soil. The capacity of the drainage store is equal to the product of the upper soil depth and its non-capillary porosity. There is no evaporation from this store. Overflow from the drainage store is allocated to the variable (P) in the runoff equation:-

$$Q = P - F \tanh (P/F)$$

where Q = runoff, pts.
P = rainfall minus moisture to fill the interception, upper soil and drainage store, pts.
F = prevailing daily infiltration capacity, pts/day.

The lower soil store contains the moisture in the subsoil which is available for evaporation and its capacity is equal to the product of the depth and available water capacity of the soil, as for the upper soil store. The store is replenished by infiltration and diminished by evaporation and percolation to groundwater. The evaporation calculations are the same as for the upper soil store, while an arbitrary daily depletion factor of 0.999 was used by Boughton to accommodate the loss to groundwater.

All calculations are on a daily basis and for the model to be applied to a particular catchment it is necessary to evaluate the following parameters:-

<u>Moisture store capacities</u>

Interception store, pts.
Upper soil store, pts.
Drainage store, pts.
Lower soil store, pts.

<u>Evaporation parameters</u>

Percentage of evaporation occurring from the upper soil zone. (Each day, evaporation occurs partly from the upper soil store and partly from the lower soil store).
Maximum evaporation rate.

<u>Infiltration parameters</u>

The parameters Fo, Fc and K in the equation:-

$$F = Fc + (Fo - Fc) \quad e^{-KS}$$

where F = rate of infiltration, pts/day.
F_c= minimum rate of infiltration, pts/day.
F_o= maximum rate of infiltration, pts/day.
S = volume of water in the lower soil store, pts.

Transmission loss

Boughton found an increase in initial loss with increasing catchment area. He considered that this loss occurred to seepage into the bed of the main stream and the defined channels over the catchment and that it was greater on large catchments, because of the more developed channel systems The loss was designated "transmission loss" and accommodated by increasing the capacity of the upper soil store.

This hypothesis has been subject to question (Boughton 1966, discussion) and its validity is examined in Section 8.

Subsoil depletion factor

The depletion factor regulates the loss of water from the lower soil store by deep seepage to groundwater. Boughton multiplied the volume of water in the lower soil store by a constant daily depletion ratio of 0.999 to provide for the loss.

The large number of parameters is a result of the detailed simulation of the runoff process. However, at the same time, this detail adds to the difficulty of applying the model to ungauged catchments.

2.2 Validity of the Boughton model

The concept of porous topsoil over dense clay subsoil implied by the Boughton model is a simplified model representation of the soil profile on actual catchments. That profile may occur on catchments, but in Eastern N.S.W. at least, a layer of transition soil is commonly located between the topsoil and clay subsoil. This anomaly has probably withheld some acceptance of the model as a valid simulation procedure.

A study of the literature on infiltration into stratified soils indicated that the model could simulate the hydrologic behaviour of small catchments, with possibly some qualification being required for large areas.

The work of Colman & Bodman (1944) and Miller and Gardner (1962) showed that infiltration and wet front advance are reduced by any type of porosity change, due to either textural or structural stratification. When this occurs a zone of positive pressure is established in the upper layer, which approaches saturation, and infiltration then proceeds under negative pressure into the lower soil. When a condition near saturation has been attained in the upper soil, runoff commences. For small catchments runoff begins when the wet front reaches the transition zone soil and positive pressure is established in the topsoil. This behaviour has been observed in the field by the author and by K.K.Watson (Univ. of N.S.W. - personal communication) and indicates that the model can accommodate the three zone soil profile, if the topsoil layer is associated with the upper soil stores, while the transition soil and subsoil are associated with the lower soil store.

Because of the increased runoff time on large catchments the behaviour is less definable and to apply the model it may be necessary to assign the transition soil partly to the upper soil stores and partly to the lower soil store.

This project is concerned primarily with small catchments, for which the model is considered to be valid and suitable for evaluation of its parameters from physical catchment characteristics, as described in the next section.

2.3 Summary of project

Models can produce satisfactory results while operating with parameter values which are far removed from those existing in nature. Simplicity and a minimum number of parameters are desirable features in a model, for too many parameters and limited data cause difficulty in identifying the effects of changing the value of a parameter.

Consequently the work was initially directed at the evaluation of the parameters via the avenue of soil physics and soil moisture relationships and from direct measurements of the components. An extensive search of the literature produced data relating to soil moisture constants (Sections 4 & 5), the rooting habits of vegetation (Section 6) and the results of infiltration and interception studies (Sections 7 & 9). This information was collated and where possible statistics calculated.

The model calculations were programmed in PL1 language (Section 10) and computer runs made for Badgerys Creek, Wagga Wagga and Scone catchments. The drainage store capacity parameter was optimised by computer runs (Section 5.2.1) and the parameter was then correlated with a climate index (Section 5.2.2). The infiltration parameters in the model were reduced from three to one and a correlation between this parameter and catchment slope was determined (Section 7).

Objective methods for estimating the parameters were prepared and then tested on data from Parwan experimental catchment (Section 11).

The conclusions and suggested future research are contained in Section 12.

3. Classification of Soils

The two important properties used for describing soils are texture and structure, and the classification of soils by these properties was investigated before proceeding to the more complex subject of soil constants.

3.1 Soil texture

Criteria have been presented, Leeper (1957, p.3), which enable the textural classification of soils to be estimated in the field on the basis of cohesion and grain size.

It was proposed to search the literature and extract soil moisture and porosity data from which statistics could be calculated and applied to soils which had been identified on catchments. This would provide a means of estimating the model parameters of upper and lower soil and drainage store capacities. As much of the available data are from U.S.A. sources, a correlation was first made of the U.S.A. and Australian systems of soil textural classification.

In decreasing coarseness of texture, soils in the two systems are as follows:-

<u>Sand</u>

Loamy sand
Sandy loam
Loam
Silt loam

<u>Silt</u>

Sandy clay loam
Clay loam
Silty clay loam
Sandy clay
Silty clay

<u>Clay</u>

Each of these (e.g. clay, clay loam) is termed a soil class. The USDA has divided the soil classes into 5 textural groups, in order of increasing amounts of clay, as listed in Table 3.1 and illustrated in Fig. 2.

Table 3.1: USDA soil textural groups

Classification	Group No.	Texture
Sand Loamy sand	1	Coarse
Sandy loam Fine sandy loam	2	Mod. coarse
Very fine sandy loam Loam Silt loam Silt	3	Medium
Clay loam Sandy clay loam Silty clay loam	4	Mod. fine
Sandy clay Silty clay Clay	5	Fine

There are two factors separating the USDA and Australian classification systems:-

(i) The different particle size limits of the sand and silt fractions.
(ii) The different proportion limits defining each textural class.

To estimate the nett effect on these differences the USDA textural groups were transposed on to an Australian textural triangle, so that by way of the 5 groups, the USDA and Australian triangles were directly comparable. It was not possible to superimpose the USDA triangle directly on the Australian triangle, because of the different particle size limits for the sand, silt and clay fractions. Transposition was achieved as follows:-

Two soils, classified as sandy loam and clay loam (USDA system), will be used to illustrate the method. The soils, of reasonable grading and selected from the literature, are plotted on a USDA triangle in Fig. 3. The gradings are shown in Table 3.2 and are converted to a suitable form for plotting on a grain size distribution graph in Table 3.3. The grain size distribution curves for the two soils are shown in Fig. 4. From these curves the percentages conforming to the Australian fraction limits were determined and are listed in Table 3.4. The figures in Tables 3.2 and 3.4 were then converted back to a form which could be readily applied to the soil triangles, as shown in Table 3.5. The positions of the soils were then plotted on an Australian triangle, Fig. 5.

This procedure was repeated for thirty soils, which were selected to determine the effect of the differences between the two classification systems on the soil class and group boundaries. The positions of the soils on the USDA and Australian triangles are shown in Figs. 6 & 7.

Table 3.2: USDA grading of two typical soils (A & B) used for correlation of USDA & Australian soil classification systems.

Fraction	USDA limits mm	% by wt. within the indicated limits	
		A Sandy loam	B Clay loam
V. coarse sand	2.0 - 1.0	3.0	2.2
Coarse sand	1.0 - 0.5	10.5	4.0
Med. sand	0.5 - 0.25	8.2	6.3
Fine sand	0.25- 0.10	25.3	8.4
V. fine sand	0.10- 0.05	22.0	9.6
Silt	0.05- 0.002	21.1	37.2
Clay	0.002	9.8	32.3

Table 3.3: Soils A & B converted for plotting on grain size distribution graph.

Dia. mm. USDA limits	% finer than given dia.	
	A Sandy loam	B Clay loam
2.0	100.0	100.0
1.0	97.0	97.8
0.5	86.4	93.8
0.25	78.2	87.5
0.10	52.9	79.1
0.05	30.9	69.5
0.002	9.8	32.5

Table 3.4: Grading of soils A & B in accordance with Aust. fraction limits.

Dia. mm. Aust. limits	% finer than given dia.	
	A Sandy loam	B Clay loam
2.0	100.0	100.0
0.2	74.5	86.0
0.02	18.0	58.5
0.002	9.8	32.3

Table 3.5: Soils A & B in suitable form for plotting on soil classification triangles

Fraction	Aust. system			USDA system		
	Limits mm	% within limits		Limits mm	% within limits	
		A. Sandy loam	B. Clay loam		A. Sandy loam	B. Clay loam
Sand	2.0-0.02	82.0	41.0	2.0-0.05	69.1	30.5
Silt	0.02-0.002	9.5	26.5	0.05-0.002	21.1	37.2
Clay	0.002	8.5	32.5	0.002	9.8	32.3

The transposed USDA textural classes, obtained by the foregoing procedure, are marked on the Australian triangle of Fig. 8. The transposed USDA textural groups are shown on Fig. 9.

The classification of soils under the Australian and USDA systems may be directly compared from Fig. 8 on a class basis, or from Figs. 2 & 9 by way of the textural groups.

To obtain an unequivocal correlation it would be necessary to repeat the transposition for a much greater number of soils and to adopt sand fractions varying from fine to coarse. However, the correlation obtained is sufficient for the required purpose and indicates that there is not a large difference between the two classification systems. The difference is greater for the coarser textured (sandy) soils than for the finer soils.

The correlations of Figs. 2, 8 and 9 enable soil constant data determined in the United States to be applied to soils identified by the Australian system.

3.2 Soil structure

The USDA Soil Survey Manual (1951, p. 225) details a method of soil structure classification based on the following three characteristics which may be determined in the field:-

(i) The shape and arrangement of the aggregates.
(ii) The size of the aggregates.
(iii) The distinctness and durability of the aggregates.

That system of classification was adopted for this project. The field determination of soil structure enabled the permeability and infiltration behaviour of the profile to be estimated. Also, the non-capillary porosity (and hence drainage store capacity) was initially estimated from a correlation between non-capillary porosity and permeability (Section 5.1.3.2).

4. AVAILABLE WATER CAPACITY

In this chapter the classification of soil pores and soil water is described (Sections 4.1 and 4.2) before proceeding (Section 4.3) to the investigation of design data for available water capacity, required for the upper and lower soil moisture stores in the model. The capacity of the upper and lower soil moisture stores is equal to the product of the respective soil zone depth and the available water capacity (AWC) of the soil.

4.1 Soil pores

The pore space characteristics of a soil depend upon its structure more than texture. Soil pores may be classified by size to come within one of the following three groups:-

(i) Non-capillary or macro-pores.
(ii) Capillary or micro-pores.
(iii) Sub-capillary pores.

Generally the larger non-capillary pores contribute to permeability, while the smaller capillary and sub-capillary pores determine the water holding characteristics of soils.

4.2 Soil water

Two classes of soil water are associated with the model parameters:-

(i) Gravitational water, located in the non-capillary pores.
(ii) Available water, held in the capillary pores.

Three points of equilibrium define the limits of the soil moisture classes as follows:-

(i) Saturation capacity)
(ii) Field capacity)....Gravitational water
(iii) Wilting point)....Available water

The terms gravitational water capacity and field capacity are analogous to the concepts of specific yield and specific retention as used in groundwater studies. Consequently the results of groundwater research were found to be of value, for example the graphical correlation of Piper (1933) between specific retention (field capacity) and moisture equivalent.

4.3 Design data - available water capacity (AWC)

A useful means of expressing available water capacity (AWC) is "inches of water/ft depth of soil." The depth of soil in the upper and lower soil zones multiplied by the corresponding AWC gives the capacities of the upper and lower soil moisture stores in the model.

Briggs & Shantz (1912) and Neal (1932) carried out early work on the variation of AWC with soil texture. They found that the AWC increased with increasing fineness of soil texture.

Typical values for the available water capacity of various soils are interspersed throughout the literature. It is very difficult to determine the weight which should be assigned to many of these values and also the textural range over which they apply. Compared with an analysis of fortuitously selected values, a complete set of data covering the entire soil textural range provides a more satisfactory basis upon which to establish design data, with an acceptable degree of accuracy.

Two suitable sources are Shockley (1955), formerly of the USDA, and the Australian Draft Spray Irrigation Code (1965). Of these, the former is the more comprehensive and, also, enquiries which were made regarding the source of the Spray Code data were not successful, at the time when this aspect was being investigated. It was therefore decided to transpose Shockley's data to the Australian textural classification system, both to check and supplement the Spray Code values.

The data of Shockley is listed in Table 4.1 and is illustrated on a USDA textural triangle in Fig. 10. This information was transposed on to the Australian textural triangle in Fig. 11, with the necessary adjustments being made for the differences between the two classification systems, by applying the correlations determined in Section 3.1 above.

The Australian Spray Code data are listed in Table 4.2 and are illustrated in Fig. 12.

The values shown in Figs. 11 and 12 compare quite well, with the exception of the fine textured soils. The Spray Code lists the available water capacity of clay and fine clay loam as 1.7 in/ft, with the latter having a range of 1.7 - 1.9 in/ft. From Fig. 11, Shockley considers these soils as having a range of 1.6 - 2.5 in/ft, and an average design value is 2.25 in/ft.

Table 4.1: Available moisture capacity - Shockley, USDA (1955)

Soil description			Available moisture ins/ft	
			Range	* Average
Fine	>40% clay	Clay, silty clay, sandy clay.	1.6 - 2.5	2.3
Mod. fine	27-40% clay	Silty clay loam, clay loam.	1.6 - 2.5	2.2
Medium	>40% silt	Silty loams, silt loam.	1.6 - 2.5	2.3
Medium	0 - 39% silt	Sandy clay loam, loam, v. fine sandy loams, sandy loams containing less than 70% sand.	1.5 - 2.4	1.9
Mod. coarse	>70% sand	Fine sandy loam and sandy loam containing more than 70% sand, & loamy fine sand.	1.0 - 1.5	1.2
Coarse	< 95% sand	Loamy sand, fine sand, coarse sand.	0.8 - 1.0	0.9

* To be used for design unless specific value is known.

Table 4.2: Available moisture capacity - Australian Draft Spray Irrigation Code (1965)

Soil	Available water, ins/ft depth of soil	
	Range	Average
Clay	1.7	1.7
Heavy clay loam	1.7 - 1.9	1.7
Clay loam	1.9 - 2.1	2.0
Light clay loam	2.1 - 2.2	2.1
Silt loam	2.1 - 2.2	2.1
Loam	1.9 - 2.1	2.0
Fine sandy loam	1.5 - 1.9	1.7
Sandy loam	1.1 - 1.5	1.3
Fine sand	0.8 - 1.1	0.9
Sand	Up to 0.8	0.6

Leeper (1957, p. 92) lists AWC values for selected South Australian and Victorian soils with the capacity of the two clays in the order of 2.6 - 3.2 in/ft.

Fleming CSIRO Aust. (1966), presumably guided by Australian experience, quotes the AWC values ex Shockley (1956) with fine textured sandy clays, silty clay and clay having a range of 1.6 - 2.5 in/ft and an average of 2.0 in/ft.

Costin et al (1964) give average AWC values in the order of 3 in/ft for meadow soils in the Kosciusko region of N.S.W.

Linsley, Kohler and Paulhus (1949 p. 126) give an AWC value of 2.3 in/ft for clay, Lehane and Staple (1953) quote 2.8 in/ft and the USDA 1957 Yearbook of Agriculture states a general range as 2.0 - 3.0 in/ft for clay.

Some time after the above work on AWC values had been completed, a table of values identical with those recommended by the Draft Australian Spray Irrigation Code was located in the NSW Dept. of Agriculture Bulletin No. P. 336 entitled "The Principles of Irrigation". The source of the table is given as an interpolation from information contained in the USDA 1955 Yearbook of Agriculture. An examination of the yearbook indicated that interpolation was probably made from the untitled figure on page 120. This same figure is also reproduced by Russell and Hurlbut (1959). However, elsewhere in the 1955 Yearbook the following AWC values are listed by various authors:-

		Soil	AWC, in/ft
Taylor & Slater	p. 375	Clays & organic soils	2.5 or more
Boswell & Thorne	p. 453	Silt loams, clay loams and clays	2.5 - 3
Hagon	p. 463	Clays	2.5

Although clay soils in Australian irrigation areas may have an AWC as low as 1.7 in/ft, this value is considered to be too low for general application. A value of at least 2.0 in/ft would be more appropriate.

It would not be difficult to combine the Australian Spray Code and Shockley's data to produce a set of round figures for use as design values, but it is considered more judicious to leave each set of data as it stands. For design purposes the appropriate value may be selected by joint consideration of the above discussion and the information in Figs. 11 and 12.

Table 5.1: Texture - specific yield data.

Textural Group USDA classification	Description	Linsley Kohler & Paulhus (1958, p. 130)	Eckis & Gross (1934)	Piper et al (1939)	Davis et al (1959)	Thomasson et al (1960) Olmsted & Davis (1961)	Mean of means	Standard deviation of means
1. Coarse	Sands: coarse medium fine Loamy sands	)) 25)	28 16	34.8 24.2	25 10	20 10	Coarse sand $\frac{62.8}{2} = 31.4$ Fine sand $\frac{36}{2} = 18.0$	3.4 2.8
		Mean value 25	22	29.5	17.5	15.0	21.8	5.2
2. Moderately coarse	Sandy loam Fine sandy loam							
3. Medium	Very fine sandy loam Loam Silt loam Silt			4.2	5	3		
		Mean value		4.2	5	3	4.1	1.4
4. Moderately fine	Clay loam Sandy loam Silty clay loam							
5. Fine	Sandy clay Silty clay Clay	 3	5)) 1)	 4.2	5 3	 3		
		Mean value 3.0	3.0	4.2	4.0	3	3.4	0.5

Table 5.2: Texture - non capillary porosity data

Textural group USDA classification	Description	Baver (1938)	Kopecky (1927)	Neal (1932)	Ayres & Scoates (1939)	Mean of means	Standard deviation of means
1. Coarse	Sands: coarse medium fine Loamy sands			19 - 28.5	24.7 23.5		
		Mean values		23.75	24.10	23.93	0.2
2. Moderately coarse	Sandy loam Fine sandy loam		12.5 - 15	10.5-19.0	20.1 18.8		
		Mean values	13.75	14.75	19.45	15.98	2.5
3. Medium	Very fine sandy loam Silt loam Silt	6.0 (13.0 (14.7 10.0	8-12.5	7.0-10.5	14.5 12.2		
		Mean values 10.92	10.25	8.75	13.35	10.82	1.7
4. Moderately fine	Clay loam Sandy clay loam Silty clay loam	9.0 13.0 9.2	3.5-6				
		Mean values 10.40	4.75			7.57	2.8
5. Fine	Sandy clay Silty clay Clay	12.0 13.5 5.5 6.0 8.0 11.5	0.4-3.0	3.5-7.0	9.6		
		Mean values 9.41	1.70	5.25	9.60	6.49	3.3

5. DRAINAGE STORE CAPACITY

Two separate approaches were used to establish design values for the drainage store capacity (DSMAX) in the model, as follows:-

(i) Estimation from soil physical properties.
(ii) Optimisation of the parameter DSMAX in the model.

The first approach (Section 5.1) was initially considered preferable on the basis that the estimated values would be near to those existing in nature. Although this was moderately successful, it was still necessary to employ optimisation of DSMAX using the computer, as described in Section 5.2.

5.1 Estimation from soil physical properties

To evaluate the parameter DSMAX in the model from soil physical properties, it is necessary to estimate the non-capillary porosity (NCP) of surface soils. The capacity of the drainage store is then obtained by multiplying the NCP by the depth of the upper soil.

The terms non-capillary porosity, gravitational water capacity and specific yield are synomynous and are used in contexts associated with soil physics, agriculture and groundwater studies respectively. Each of these three sources was investigated in an endeavour to obtain design data. Specific yield (groundwater) and subsoil (agricultural) data will be presented before proceeding to the more complex subject of surface soils.

5.1.1 Specific yield

Specific yield data from various groundwater investigations is presented in Table 5.1. Most studies in this field have considered only soil texture and this basis is used to obtain a rough estimate of specific yield. For both decreasing size and uniformity of the soil particles, specific yield has a definite tendency to decrease. For a coarse sand the specific yield may be as high as 35% and for a pure clay, close to zero.

5.1.2 Subsoils

Table 5.2 shows NCP data generally from agricultural investigations and regarded as for material in a subsoil condition. For the medium to fine soils, the values exceed those in Table 5.1 with respect to both mean and variance. This is attributed directly to the effects of soil structure. For surface soils, vegetation would be expected to increase the structure effect still further.

The subsoil data of Free et al (1940) listed in Table 5.3 permits a closer examination of NCP. These values are based on total porosity minus moisture equivalent and represent measurements made on 68 catchments spread over the United States. An analysis of variance and significance test on these data showed that the variation in NCP between texture is significant at the 2.5% level. The data were arranged into classes and the Chi-square test indicated a "very good" fit to a normal distribution wi mean 14.4% and standard deviation 7.1%. These results may be compare with those obtained later for surface soils.

Table 5.3: NCP of subsoils: Data ex Free et al (1940)

	Texture				
	Silt loam	Clay and clay loam	Gravelly silt loams	Sandy loams	Loams
	4.6	13.3	20.2	13.5	22.1
	0.5	7.3	17.9	16.3	10.1
	11.6	12.6	25.2	24.2	18.3
	9.2	8.7	24.3	8.3	22.3
	18.9	7.1	15.9	8.5	8.1
	22.3	5.3	8.2	6.8	
	17.3	7.4	21.8	11.0	
	12.8	15.9	18.4	2.0	
	14.3	16.9	27.5	17.8	
	11.8	9.5	21.7	12.5	
	13.3	11.2	15.1	16.3	
	6.3	12.6		22.0	
	5.6	10.2		25.6	
	19.6	10.3			
	5.9	5.0			
	24.1	6.5			
	29.2	17.1			
	28.1				
	30.4				
	11.6				
	7.6				
Mean	12.8	10.2	20.2	13.5	18.3

5.1.3 Surface soils

Preliminary work revealed that surface soil NCP would be a difficul parameter for which to establish design data, due to its variability, limit data and the problem of defining or measuring NCP.

The definition of NCP and the significance of factors which affect this soil property were examined (Section 5.1.3.1). Statistics were calculated from available data and attempts made to correlate NCP with physical properties (Section 5.1.3.2).

5.1.3.1 Definition and variability of surface soil NCP

The NCP of soil may be defined in several ways:-

(i) The pores greater than 30 μ in diameter.
(ii) The pores drained up to the flex point on the "moisture content Vs pF" curve (pF is the log of the soil moisture tension). Typical tensions expressed in terms of water column height are:-

40 cm	(pF 1.6)
50 cm	(pF 1.78)
100 cm	(pF 2.0)

(iii) Total porosity minus field capacity. (Field capacity is the moisture content to which a saturated soil, in the field, will drain in 2-4 days).

(iv) Total porosity minus moisture equivalent adjusted for texture. (Moisture equivalent is the moisture content of a soil sample which has been subjected to a field of 1000 times gravity for 30 minutes in a centrifuge).

The investigations of Dreibelbis and Post (1940, 1943) enable a study of the differences in estimated NCP by using methods (ii) and (iv) above. The data relates to 5 small U.S.A. catchments (1-2 acres) situated in close proximity, but with different soils and land use.

The initial data were read from graphs and tables presented by the above authors and, using this, Table 5.4 shows the values of NCP calculated from tension measurements (method (ii)) and Table 5.5 the estimation of values based on moisture equivalent adjusted for texture (method (iv)). The estimated NCP data are summarised in Table 5.6.

Table 5.4: Calculation of surface soil NCP from tension measurement
Data ex Dreibelbis and Post (1943)

Catchment No.	Total porosity %			NCP %								
				40 cm tension			60 cm tension			90 cm tens		
	May	Jly	Oct	May	Jly	Oct	May	Jly	Oct	May	Jly	O
131	55.0	55.2	49.7	20.4	20.8	18.2	22.5	23.6	20.0	25.6	26.1	22
102	48.0	49.0	49.7	10.1	10.6	13.0	12.3	12.5	15.3	15.0	14.9	18
109	51.2	53.6	52.1	10.9	14.5	14.4	12.6	16.3	16.9	15.2	18.8	19
104	49.0	49.0	-	7.8	11.5	-	9.5	11.0	-	12.0	13.3	-
123	49.0	47.9	54.0	10.7	10.0	13.1	12.3	11.5	15.5	16.6	14.0	17

Table 5.5: Calculation of surface soil NCP from porosity minus moistu
equivalent: Data ex Dreibelbis & Post (1940)

Catchment No.	Volume weight %	ME % wt	ME % vol	ME adjustment factor for texture. Piper(1933)	Adjusted ME % vol	Total pore space %	NCP % vol.
131	1.13	19.4	22.0	0.96	21.1	55.2	34.1
102-104	1.43	20.5	29.4	0.95	27.0	42.6	15.6
102-104	1.37	23.0	31.6	0.94	29.7	45.4	15.7
109	1.25	24.3	30.4	0.93	28.3	51.2	22.9
123	1.22	25.8	31.5	0.92	29.0	54.5	25.5

An analysis of variance of the 42 NCP values based on tension measurement gives the results shown in Table 5.7.

All effects are very significant, with the catchment and method of measurement effects being considerably greater than the month effects.

Of the tension data, the 96 cm measurements have the closest agreement with the values estimated from the adjusted moisture equivalent. However, further analysis of variance showed the variation between these two methods of measurement to be significant at the 5% level.

Table 5.6: Surface soil NCP data, calculated from both tension measurements and porosity minus ME adjusted for texture

Catchment No.	Description	Based on pores drained at 40 cm tension			Based on pores drained at 60 cm tension			Based on pores drained at 96cm tension			Based on total porosity minus ME adjusted for texture
		May	Jly	Oct	May	Jly	Oct	May	Jly	Oct.	
131	Muskingum loam, - woodland	20.4	20.8	18.2	22.5	23.6	20.0	25.6	26.1	22.5	34.1
102	Muskingum silt loam - pasture @ 4" high	10.1	10.6	13.0	12.3	12.5	15.3	15.0	14.9	18.1	15.7
109	Muskingum silt loam - cultivated	10.9	14.5	14.4	12.6	16.3	16.9	15.2	18.8	19.4	22.9
104	Muskingum silt loam -pasture @ 3" high	7.8	11.5	-	9.5	11.0	-	12.0	13.3	-	15.7
123	Keene silt loam -cultivated	10.7	10.0	13.1	12.3	11.5	15.5	16.6	14.0	14.8	25.5

Table 5.7: Results of analysis of variance of NCP data

Item	Sum of squares	df	Estimated variance	Level of significance of effect, %
Between catchments	6.08	4	1.52	0.5
Between methods of measuring NCP	1.42	2	0.71	0.5
Between months	0.53	2	0.265	0.5
Residual	0.42	33	0.014	
Total	8.45	41		

To examine the effect of texture on surface soil NCP, an analysis of variance was made on the data of Free et al (1940), listed in Table 5.8. These surface soil NCP values are based on total porosity minus moisture equivalent and were determined from measurements made on 68 United States catchments. The F-test showed that the difference between textures was not significant at the 5% level.

In summary, the statistical analysis in this section has indicated that:-

(a) the following variations in surface soil NCP may occur;

  (i) Very significant variation between catchments in the same vicinity with similar soils but having different surface treatments.

  (ii) Very significant variation between methods of measuring NCP.

  (iii) Very significant variation in the NCP of a given surface soil at different times of the year.

(b) texture is not a suitable property upon which to base estimates of the NCP of surface soils.

Table 5.8: Surface soil NCP data ex Free et al (1940)

NCP of surface soil, %				
Silt loam	Clay and clay loam	Gravelly silt loams	Sandy loams	Loams
36.3	36.7	35.0	35.5	30.4
32.0	34.4	34.5	32.7	23.7
31.0	28.7	32.6	32.4	22.0
30.8	28.4	28.7	27.7	19.3
30.5	27.9	26.9	26.3	17.2
30.1	27.0	25.5	24.2	
29.6	26.6	25.4	23.4	
29.4	25.3	25.0	22.8	
29.2	25.1	22.7	21.3	
28.2	23.8	19.1	20.6	
27.8	23.7	15.2	19.5	
27.1	19.9			
26.7	19.8			
26.5	17.8			
24.3	17.6			
24.2	16.9			
23.7	14.0			
23.2				
22.5				
21.8				
21.6				
13.3				

It was accepted that the better basis for estimating NCP (tension, or porosity minus ME) could not be determined and that this soil property would have considerable variance. (The most satisfactory method for measuring surface soil NCP is by field saturation and drainage, as described by Black (1956), but no data on that basis were located).

Section 5.1.3.2 describes three attempts to correlate NCP with physical properties. The values of NCP used in that work were based on both tension (1st and 2nd approach) and porosity minus ME (1st and 3rd approach) measurement.

In section 5.2 the problem of defining NCP was circumvented by optimising the parameter DSMAX, using the computer.

5.1.3.2 Correlation of surface soil NCP with physical properties

Three separate approaches were employed in an endeavour to associate surface soil NCP with physical catchment properties. A description of each attempt will be given.

First approach - arbitrary table

The initial attempt to relate surface soil NCP to physical properties was made before the data of Free et al and Dreibelbis and Post had been located. A study of the literature and Tables 5.1 and 5.2 above indicated that soil texture, structure and compaction and vegetation would be significant factors. From the data of Wollny (1877), reproduced by Bayer (1956, p. 185), and Tables 5.1 and 5.2, the range of surface soil NCP was estimated to be 3 - 35%, increasing with coarseness of soil texture. The effects of structure were estimated from published reports on the soil structure - permeability relationships, O'Neal (1949) and Donahue (1961), and an estimated relation between permeability and NCP using the data of Bendixen and Slater (1946), Bendixen et al (1948). The effects of percent vegetal cover on NCP were assumed to be linear and compaction effects to be curvilinear.

Table 5.9 illustrates the method of derivation with five classes of NCP and a "percentage effect" assigned to each variable. The NCP was estimated by summing the contributions for texture, structure, vegetal cover and compaction in the table. The table was tested by estimating the NCP of surface soils described in the literature and not used in the derivation, with good results. However, the method was not considered satisfactory because of the arbitrariness of the recommended percentage effects and the method's many assumptions.

Second approach - NCP Vs percolation rate correlation

The second approach was aimed at eliminating some of the arbitrary assumptions in the first approach. Several workers have correlated the constant percolation rate of a soil with the percentage of pores drained when a 3" diameter by 3" thick core was subjected to 60 cm tension for 1 hour. A search of the literature produced data from six separate sources and this is plotted in Fig. 13. A least squares regression of "percolation rate" on "pore space drained" produced the line marked A in Fig. 13, which conforms to the equation:-

$$\log F = 1.32 \log P - 1.08$$

where
F = percolation rate, in/hr.
P = pore space drained, % of volume.

Table 5.9: Surface soil NCP estimation table.

NCP class Class value %	1 35	2 25	3 16	4 7	5 3
Textural group (see Fig. 9)	1	2	3	4	5
Texture (effect 35%)	12.3	8.8	5.6	2.5	1.1
Structure (effect 30%)	10.5	7.5	4.8	2.1	0.9
a. Type	1. Crumb 2. Single grain	Granular	Blocklike Prism-like	Blocklike Prism-like	1. Platy 2. Massive
b. Grade	1. Weak 2. Structureless-single grain, non-coherent	Weak	Moderate	Strong	1. V. strong 2. Structureless massive coherent
c. Size of visible pores		Mod. coarse	Medium	Fine	None
% of basal area covered	100	75	50	25	7.5
Vegetal cover (effect 20%)	7.0	5.3	3.5	1.7	0.5
Compaction (effect 15%)	5.2 Loose	3.4 Mod. loose	2.1 Medium	0.7 Mod. dense	0.5 Dense

Note: Add values underlined to estimate NCP.

The coefficient of correlation (r) was 0.75 and Student's test showed the correlation to be significant at the 0.5% level. The 95% confidence limits for the population coefficient of correlation (ρ) were 0.66 and 0.83. These statistics indicated that the correlation was acceptable.

The results of Bendixen and Slater (1946) listed in Table 5.10 were used to estimate a relation between percolation rate and NCP, from Fig. 13. These workers presented values of pores drained at 1 hour and near equilibrium, for cores 3" dia. by 3" thick, under 60 cm tension. The 1 hour values were plotted on line A, as in Fig. 14. From these points the corresponding estimated values of "pores drained at equilibrium" were extended horizontally and plotted. A least squares regression of "percolation rate" on "pores drained at equilibrium" produced line B, which is the estimated relation of "percolation rate Vs NCP".

Table 5.10 Estimation of F Vs NCP relation, using data ex Bendixen and Slater (1946)

Pores drained, % vol.		Percolation rate, in/hr (estimated)
Drained in 1 hour	Drained to equilibrium (estimated)	
From Bendixen & Slater (1946)		From Fig. 14
3.6	5.0	0.43
5.0	8.3	0.68
5.3	8.0	0.72
5.7	10.5	0.80
8.2	13.3	1.30
12.0	17.2	2.18
12.3	22.4	2.28
0.5	0.7	0.032
1.08	1.78	0.089
1.65	2.25	0.155
1.80	2.85	0.176
3.90	5.25	0.490

Table 5.11: Estimation of Soil Permeability Class from Identifiable Soil Properties.

Structure or structural condition	Principal characteristics: Shape and overlap of aggregates — Relation of horizontal and vertical dimensions	Principal characteristics: Shape and overlap of aggregates — Overlap, direction, and amount	Principal characteristics: Visible pores	Principal characteristics: Texture	Permeability class (7 Class System)
Fragmental	Hor. >Vert.	Hor. 25–50%	None	Heavy	Very slow
	Hor. >Vert.	Hor. 25–50%	Few	Hvy.–Mod. hvy.	Slow
	Hor. >Vert.	Hor. 0–25%	Mod. few	Hvy.–Mod. hvy.	Mod. slow
	Equal	Oblique	Moderate	Hvy.–Mod. light	Moderate
	Eq. or V. >Hor.	Oblique	Many	Hvy.–Mod. hvy.	Mod. rapid
	Eq. or V. >Hor.	Oblique	Many	Mod. hvy.–med.	Rapid
	Eq. or V. >Hor.	Oblique	Very many	Hvy.–Mod. hvy.	Very rapid
Platy	Hor. > Vert.	Hor. 25–50%	None	Hvy.–Mod. hvy.	Very slow
	Hor. > Vert.	Hor. 25–50%	Few	Med.–Mod. hvy.	Slow
	Hor. > Vert.	Hor. 0–25%	Mod. few	Heavy–Light	Mod. slow
	Hor. > Vert.	Hor. 0–25%	Moderate	Med.–Mod. hvy.	Moderate
Nuciform	Equal	Oblique	Moderate	Mod. light–hvy.	Moderate
	Eq. or V. > Hor.	Oblique	Many	Medium–Heavy	Mod. rapid
	Eq. or V. > Hor.	Oblique	Many	Mod. light–hvy.	Rapid
	Eq. or V. > Hor.	Oblique	Very many	Mod. lt.–Mod. hvy.	Very rapid
Cubical blocky	Equal	Hor. 25–50%	None	Mod. hvy.–hvy.	Very slow
	Equal	Hor. 25–50%	Few	Mod. hvy.–hvy.	Slow
	Equal	Hor. 0–25%	Mod. few	Heavy–Medium	Mod. slow
	Equal	Hor. 0–25%	Moderate	Heavy	Moderate
	Equal	Hor. 0–25%	Many	Heavy	Mod. rapid
	Equal	Hor. 0–25%	Very many	Heavy–Mod. hvy.	Rapid
Prismatic	Vert. > Hor.	Hor. 0–25%	None	Mod. hvy.–hvy.	Very slow
	Vert. > Hor.	Hor. 0–25%	Few	Heavy–Mod. hvy.	Slow
	Vert. > Hor.	Hor. 0–25%	Mod. few	Medium–Heavy	Mod. slow
	Vert. > Hor.	Hor. 0–25%	Moderate	Heavy–Medium	Moderate
	Vert. > Hor.	Hor. 0–25%	Many	Medium–Heavy	Mod. rapid
	Vert. > Hor.	Hor. 0–25%	Very many	Mod. hvy.–hvy.	Rapid
	Vert. > Hor.	Hor. 0–25%	Very many	Medium	Very rapid
Single grain	Flat sand grs Hor. > Vert.	Hor. overlap sand grains	Moderate	Mod. light	Moderate
	Flat sand grs Hor. > Vert.	Some hor. overlap sand grains	Moderate	Mod. light	Mod. rapid
	Mostly sand grains Equal	Oblique overlap sand grains	Many	Light	Rapid
	Round grains Equal	Oblique overlap sand	Very many	Very light	Very rapid
Massive	None	None	None	Heavy	Very slow
	None	None	Few	Med.–Mod. hvy.	Slow
	None	None	Mod. few	Hvy.–Mod. light	Mod. slow

(from O'Neal, 1952).

Line B is reproduced in Fig. 15 together with the seven class system for classifying permeability. The permeability class of a soil may be estimated from Table 5.11 (O'Neal, 1952) and the NCP may then be estimated from the correlation in Fig. 15.

The NCP estimated by this method is based on the estimated drainage to equilibrium under 60 cm tension and insufficient data are available to correlate these values of NCP with values determined by the other available methods of measurements. Also, the information in Table 5.11 relates to subsoils and not to surface soils. However, from an applied viewpoint this method was found to be of assistance when examining soils of low NCP in the field.

Third approach - statistics from NCP data

The third approach involved the calculation of mean NCP values (based on porosity - adjusted moisture equivalent) from the NCP data and surface soil descriptions of Free et al (1940), Dreibelbis and Post (1940) and Shively and Weaver (1939, p. 24).

The data of the first two workers have been previously presented in Tables 5.8 and 5.6. An analysis of variance indicated that these data (i.e. Free et al and Dreibelbis and Post) could be regarded as from the same population, for the between sources effects were not significant at the 5% level. The two sets of data were grouped into frequency classes and the Chi-square test revealed a "very good fit" to a normal distribution with mean 25.2%, standard deviation 5.8%, and 90% confidence interval of 15.8 - 34.6%.

The NCP data and soil descriptions of Free et al and Shively and Weaver were sorted and the information in Tables 5.12 and 5.13 extracted. The mean and standard deviation of the NCP value for dense grass-crumb structure was calculated as 33.9% $\pm$ 1.8% and for range land 26.0% $\pm$ 3.6%.

Table 5.12: Estimation of NCP for dense grass-crumb structure (NCP based on porosity minus ME)

Source	Description		NCP, %
	Soil	Vegetation	
Free et al Catchment No. 25	Brownish grey, quite friable silt loam.	Timothy, orchard grass and clover pasture for last 2 years	32.6
Free et al Catchment No. 24	Dark brown, gravelly silt loam.	Dense blue grass sod, which probably had not been disturbed for many years	34.5
Free et al Catchment No. 140	Dark reddish brown clay loam with crumb structure.	Fruit orchard with small grain & vetch as winter cover crop on site at time of run. Past winter cover crop, cowpeas	36.3
Shively and Weaver (1939 p. 24)	Surface 6" loam soil. Excellent crumb structure, very porous and receptive to water.	Covered with little blue stem.	32.3
		Mean	33.9

Table 5.13: Estimation of NCP for range land (NCP based on porosity minus ME)

Source	Description		NCP, %
	Soil	Vegetation	
Free et al Catchment No. 131	Compact brownish yellow clay.	Range land.	19.8
do. 133	Brown clay loam.	Range land. Moderate grass cover, sparsely timbered.	23.8

Table 5.13 (cont'd.) Estimation of NCP for range land (NCP based on porosity minus ME)

Source	Description		NCP, %
	Soil	Vegetation	
Free et al Catchment No. 134	Brown clay loam.	Range land. Sparse cover of grass.	25.3
Free et al Catchment No. 137	Light brown sandy loam.	Range land.	26.3
Free et al Catchment No. 132	Rather loose greyish-brown clay.	Range land.	27.0
Free et al Catchment No. 136	Light brown sandy clay loam.	Range land.	27.7
Free et al Catchment No. 135	Very light brown loose sandy loam.	Range land. Covered with sparse stand of grass.	32.4
		Mean	26.0

These statistics should provide a reasonable estimate of NCP for the dense grass-crumb structure and range land conditions. However, estimates based on the second approach (tension measurements) would be different and this was not considered satisfactory.

Consequently, a fourth method of determining the drainage store parameter (DSMAX) was pursued. This involved optimisation of the DSMAX parameter in operation of the model for gauged catchments. The objective was to correlate the optimum DSMAX values with a physical catchment characteristic. The characteristic chosen was a climate index, which was intended to represent the geographic location, vegetal and topsoil conditions of catchments. This approach is described in Section 5.2.

5.2 Optimisation of DSMAX using the computer and correlation with a climate index

The work described in this section was effected late in the project and was devised to overcome the problems associated with estimating DSMAX from the separate parameters of NCP and upper soil zone depth.

The optimisation of DSMAX for Scone, Wagga Wagga and Badgerys Creek catchment data is described in Section 5.2.1.

The correlation of the optimum values of DSMAX with a catchment climate index is presented in Section 5.2.2.

5.2.1 Derivation of optimum DSMAX values

The mean NCP values derived immediately above and measured upper soil zone depths were used to estimate DSMAX when the initial computer runs were made with the model on Scone, Wagga Wagga and Badgerys Creek catchment data. The other model parameters were also estimated from physical catchment properties.

It was apparent that the prediction of runoff could be improved by obtaining better estimates of DSMAX and the infiltration curves.

With the other parameters held constant, second and third estimates of DSMAX were made and infiltration curves derived from the computer results as described in Section 7.4. On the second or third run the infiltration curves became reasonably stable, but it was considered that the prediction of runoff could be further improved by obtaining better estimates of DSMAX and it was decided to optimise this parameter.

With all other parameters held constant, the model was operated on the computer using a range of values for DSMAX and the predicted runoff results were collated to find the optimum value of DSMAX. It was found that the optimum value varied widely, depending upon the optimisation criterion.

The criteria employed were:-

(i) (Σ Q recorded - ΣQ calculated) to be zero.

Here the disadvantage was that one large error could outweigh many small errors.

(ii) (Σlog Q recorded - Σ log Q calculated) to be a minimum.

The aim of this method was to reduce the weight of large flows and produce an equal distribution of the plotted points on either side of the 45^{o} line on a log-log graph of "Q recorded Vs Q calculated".

(iii) (Σ log Q recorded $-\Sigma$ log Q calculated) to be a minimum.

Designed to reduce the weight of large flows and to give the closest fit of the plotted points to the 45^{o} line on a log-log graph of "Q recorded Vs Q calculated."

The results of the three methods are shown in Figs. 16-24. It may be noted that for criterion (iii) the curves in Figs. 18, 21 and 24 do not cross the X-axis, because absolute values are specified. The optimum values of DSMAX obtained by the three methods are summarised in Table 5.14.

Table 5.14: Optimum values of DSMAX (pts) from computer runs

Catchment	Criterion		
	(i)	(ii)	(iii)
Scone	70	64	78
Badgerys Creek	56	63	80
Wagga Wagga	46	18	28

Criterion (i) is simple and directly specifies that the estimated and recorded runoff totals be equal. This criterion also produced optimum values of DSMAX which were more consistent with the physical catchment conditions than the other methods.

In Section 5.2.2 there was shown to be a very significant variation in topsoil NCP with season of the year. This would produce similar variation in the drainage store capacity (DSMAX) and the effect would be greater over a period of years with marked differences in annual rainfall. An optimum value of DSMAX represents the average condition of a catchment during the period for which it was derived. The model would not be expected to predict all runoff events accurately, but would over-estimate some and under-estimate others, with the effect balancing over a period.

For this reason, criterion (i) was considered to be the most realistic and was adopted.

The final infiltration curves presented in Section 7, for the three N.S.W. catchments, correspond with the optimum values of DSMAX determined by criterion (i).

5.2.2 Correlation of DSMAX with climate index

The optimum values of DSMAX and catchment descriptions are listed in Table 5.15.

The NCP of the three catchments could be determined by dividing the derived DSMAX values by measured catchment upper soil zone depth. However, for design purposes it is considered preferable to use direct values of DSMAX, rather than estimate the two components of NCP and topsoil depth separately. In addition to the problems already discussed in determining NCP, field work on the above three catchments indicated that topsoil depth is also difficult to estimate accurately over a catchment. For example, the mean and standard deviation of the topsoil depth on Badgerys Creek was measured and calculated as 2.37 ± 1.23 ins, and with an uncertain estimate of NCP the resulting value of DSMAX would not be very accurate.

Table 5.15: Optimum values of DSMAX and catchment description

Catchment	Adopted optimum value of DSMAX	Catchment description		
		Topsoil structure	Vegetation	Climate
Wagga Wagga	46	Fairly dense structure	Very sparse vegetation, few roots	Annual rain. 22.0 in. Annual evap. 45.0 in. Many dry periods (For period 1951-59. Calculated from W. Boughton's data)
Badgerys Creek	56	Varies from crumb to massive	Rangeland. Fair vegetal cover with some sparse areas.	Annual rain. 24.5 in. Annual evap. 39.7 in. (For period 1957 -59. Calculated from W. Boughton's data.
Scone	70	Similar to Badgerys Ck. but with a greater proportion of crumb structure.	Good vegetal cover over most of catchment with some sparse areas.	Annual rain. 28.5in. Annual evap. 38.5 in. (For period 1958-63. Annual rainfall and evaporation values supplied by S.C.S. Scone).

As discussed later in Section 6, root habits are related to climate. Consequently topsoil depth and NCP and the dependent DSMAX are also related to climate and a realistic approach would be to derive and collate values of DSMAX based on climatic regions for natural grassed catchments. With sufficient data, land use could also be included as a parameter affecting DSMAX.

For the limited data of this study a climate index was estimated for each of the three catchments listed in Table 5.15. The climate index (C) was defined as the ratio of mean annual rainfall to mean annual pan evaporation, over the period of record for which the optimum value of DSMAX was derived.

The ratio of long term rainfall to long term evaporation was not used, because the value of DSMAX for a particular catchment varies with time and the optimum values of DSMAX in Table 5.15 are really averages for the period of record used in their derivation. The very significant variation of NCP with season of the year, shown in Section 5.1.3.1, emphasises this point. If the model was operated on a 20 year record for Scone catchment, then the 20 year value of C should be used to represent the average catchment condition during that period, and this would differ from the value of C derived for a six year period in this study.

For the three N.S.W. catchments, the annual rainfall, evaporation and climate index values, for the periods of record which were used are shown in Table 5.16. A linear least square regression of C on DSMAX produced the correlation in Fig. 25. The equation of the line is DSMAX = 94.7C + 0.97, with a coefficient of correlation of 0.99.

For the test run on Parwan Weir catchment data, described in Section 11, the climate index was calculated from recorded rainfall and estimated average annual evaporation and DSMAX then estimated from Fig. 25.

Descriptions of the soil and vegetal condition of Parwan Weir catchment were also considered, as a check to ensure that the value of DSMAX estimated from Fig. 25 was reasonable.

Although the climate index defined above was satisfactory in this study, a more complex definition could be required for areas with less uniform rainfall distribution. This is because a marked seasonal rainfall pattern encourages deep rooting of vegetation to enable survival during the following dry period.

A possible expression for the climate index, based on a three monthly time period, is :-

$$C = \frac{P_1}{E_1} + \frac{P_2}{E_2} \; . \; . \; \frac{P_n}{E_n}$$

where P_1 = rainfall during the first 3 month period, in.
P_2 = " " " second " " , in.
E_1 = pan evaporation during the first 3 month period, in.
E_2 = " " " " second 3 month period, in.

For indices of climate on a more complex physical basis attention is drawn to a literature survey by Leeper (1950).

Table 5.16: Climate index derivation

Year	Wagga Wagga *		Badgerys Ck. *		Scone +	
	P	E	P	E	P	E
1951	17.93	48.75				
1952	25.71	46.41				
1953	20.19	47.09				
1954	21.27	45.87				
1955	25.21	40.06				
1956	37.49	39.79				
1957	14.88	46.91	14.98	42.80		
1958	17.99	44.11	26.44	37.70	27.40	38.87
1959	16.48	45.92	32.18	38.70	25.85	34.02
1960					25.11	36.12
1961					26.79	38.87
1962					29.20	43.47
1963					36.48	39.67
Mean	21.90	44.99	24.53	39.70	28.47	38.50
Climate index	0.488		0.617		0.741	
Optimum DSMAX	46		56		70	

P: Annual rainfall, ins.
E: Annual pan evaporation, ins.
* Estimated from data of Boughton (1965).
\+ Information supplied by S.C.S. Scone.

5.3 Summary

The lack of data, variability and difficulty in defining NCP reduce the certainty with which design values can be determined for this soil property.

The values calculated in the third approach above (Section 5.1.3.2) are considered to offer the most suitable avenue for estimating NCP.

These values are on a porosity minus ME basis, and the NCP of surface soils was shown to be normally distributed with mean 25.2%, standard deviation 5.8% and 90% confidence interval 15.8 - 34.6%. The mean NCP for dense grass-crumb structure was calculated as 33.9% and for range land 26.0%.

However, because of the problem of defining NCP and the added difficulties in estimating upper soil zone depth, it is considered preferable to estimate the value of DSMAX directly. In Section 5.2, optimisation of DSMAX using the computer produced values for this parameter of 46 for Wagga Wagga catchment (sparse vegetation, dense structured topsoil), 56 for Badgerys Creek (medium vegetation and topsoil structure), and 70 for Scone (more prolific vegetation and more open structured topsoil). These optimum values were correlated with a climate index, for climate, vegetation, root habits, the depth and structure of the upper zone soil, and the value of DSMAX are all interdependent.

The recommended design procedure is that the climate index be determined and DSMAX then estimated from Fig. 25. If practicable the estimated value should be checked, by field inspection and a second estimate based on measured upper soil zone depth and the statistical values of NCP presented in the third approach.

The correlation in Fig. 25 is based on limited data and for this aspect to be improved it will be necessary for the model to be applied to the rainfall-runoff data from a large number of catchments. Design values could then be established for combinations of climatic region (or a climate index) and land use.

6. UPPER AND LOWER SOIL ZONE DEPTHS

Most of the work described in this chapter was undertaken prior to computer runs being made with the model. However, to maintain technical continuity, the results from computer runs using real catchment data were included in the final sections of the chapter.

In the model the soil profile is considered in two separate parts:-

(a) Upper soil zone.
(b) Lower soil zone.

The upper soil zone is represented by two soil moisture stores:-

(i) Upper soil store - contains the available water in the upper soil zone. The capacity of this store is represented by the parameter USMAX in the model and is the product of the upper soil depth and the available water capacity (AWC) of the soil.

(ii) Drainage store - contains the gravitational water in the upper soil zone. The drainage store capacity is represented by the parameter DSMAX in the model and is the product of the depth and gravitational water capacity (or NCP) of the upper soil.

The lower soil zone is represented by one soil moisture store:-

(i) Lower soil store - contains the available water in the lower soil, has a capacity represented by SSMAX in the model, and is the product of the depth and available water capacity of the lower soil.

Data have been presented which enable the available water capacity (Chapter 4) and NCP (Chapter 5) of soils to be estimated. The research described in this chapter was aimed at establishing design values for the upper and lower soil zone depths, which could be combined with the appropriate soil moisture constant (AWC or NCP) to estimate the upper and lower soil store and drainage store capacities.

A study of the model's construction indicated that the following two depths in the soil profile would specify the limits of the upper and lower soil zones:-

(i) The root zone depth (determines the depth from which moisture is removed by evapotranspiration, thus defining the total depth of the soil zones).

(ii) The division between the upper and lower soil zones.

In Section 6.1 a literature survey on the rooting habits of vegetation is followed by data on root depths. The depth to which evaporation can penetrate in removing soil moisture from bare soil is then investigated (Section 6.2). The field method of determining the division between the soil zones is discussed (Section 6.3) and the chapter is completed with information from the results of computer runs (Section 6.4).

6.1 Rooting habits of vegetation

Some significant variables which affect the depth of roots are:-

(i) plant type and age;
(ii) soil characteristics such as texture, structure, compaction, aeration and fertility;
(iii) level of the water table; and
(iv) climate and nature of the annual rainfall.

This number of variables suggests that root depths under natural conditions may cover a very wide range and be extremely difficult to estimate. However, the range is reduced by the following:-

(i) Although the maximum depths of roots vary widely, the effective or average working depths are much more uniform.

(ii) Roots will not penetrate into soil having a moisture content below the wilting point. Thus, if the maximum depth of moisture penetration is estimated, then this determines a limiting depth for plant roots.

(iii) Natural vegetation achieves adjustment with its environment, both with respect to different species and in relation to climatic and soil conditions.

These points are expanded in the next section.

6.1.1 Adjustment of roots to environment

Roots adjust to the available soil moisture. Excluding groundwater, the availability of soil moisture is dependent upon the different species of vegetation, soil texture, rainfall and evaporation. Each variable will be discussed separately.

(i) Species of vegetation - the root patterns of the various species can adjust so that most of the available moisture supply is obtained at a different depth for each species. For example grass may extract moisture from the top 2 ft, scrub from 2-4 ft and large trees deeper still.

(ii) Texture of soil - governs the available water capacity and therefore the amount of water stored within a given depth. The depth of roots increases for increasing coarseness of soil texture, with other conditions constant.

(iii) Rainfall - generally the root depth increases (spread decreases) as the amount of rainfall increases. This proceeds until the moisture supply exceeds the plant requirements, then the root depth decreases. With alternate wet and dry seasons the roots are deep for drought survival, while in arid areas roots are shallow and have a wide spread.

(iv) Evaporation - the roots adjust to the amount and rate of moisture removal by evaporation from the soil. Low evaporation and adequate rainfall promote shallow root depths while high evaporation and seasonal rainfall encourage deeper rooting for drought survival.

The following publications describe the climate and soils of New South Wales and were used to examine the relationship between root depths, soil types and climate:-

Climate:	Aust. Bureau of Meteorology	(1966)
	Aust. Dept. of National Development	(1952)
	Hounam	(1961)
Climatic regions:	Anderson	(1956)
	Bell	(1963)
	C.S.I.R.O. Aust.	(1960)
	Aust. Dept. of National Development	(1954)
Soils:	Northcote	(1960)
	Prescott	(1944)
	Stace	(1961)
	Stephens	(1956)
Vegetation regions:	Aust. Dept. of National Development	(1955)

6.1.2 Root depths

Information regarding root depths is assembled in Table 6.1. The data indicate the general order of depths but are not sufficient to enable the calculation of design values for the climatic regions of New South Wales. Several points to be noted from the table are:-

(i) Most grasses have a concentration of roots (50% or more) in the top 0.5 of soil.

(ii) For a wide range of vegetation, 70-90% of the roots are included in the top 2 ft of soil.

(iii) The expected range for effective root depths of light natural vegetation is 3" - 3 ft.

Table 6.1: Root depths of grasses

Source	Location	Root depths, ft		Remarks
		Native grasses	Improved pasture	
Boughton (1965 p.48)	N.S.W. Eastern podsol area	2.5-3		Discussed subject with Botanists at University of New South Wales and University of Sydney.
S.C.S. of N.S.W.	Wellington N.S.W.	0-1.5		
do.	Inverell N.S.W.	2.2-2.8		
do.	Wagga Wagga N.S.W.	0.3-0.5	0.3-0.5	Average root depth later measured as 7" with most of the roots in the top 2".
do.	Cowra N.S.W.	0.5	0.33	General depth containing major proportion of the roots.
Draft Aust. Spray Irrign. Code (1965)	Aust. Irrigation conditions		1-2.5	Greater depths for lighter soils and lesser depths for heavier soils.

Table 6.1 (cont'd.) Root depths of grasses

Source	Location	Root depths, ft.		Remarks
		Native grasses	Improved pasture	
Ozanne et al (1965)	Western Aust.	0.8	1.3	Effective root depths, from field experiments in uncompacted sand. The effective root depth contains 90% of the roots.
Laverton (1964, p. 21)	England	0.8-1.2 1.5-2.0		Short grass) effective root depths Long grass)
U.S.D.A. Soil Survey Manual (1951, p. 250)	U.S.A.	0.5 (65-80%)		For most grasses 65-80% of the roots live in the surface 0.5 ft. Other grasses, although with a large proportion of roots in the surface layer, have roots to 6-10 ft and deeper.
Shively & Weaver (1939, p. 23)	U.S.A.	0.5 (60-70%)		For grasslands, 60-70% of roots in surface 0.5 ft and remainder distributed to 4.0 ft depth.
Baver (1956 p. 445)	U.S.A.	0.5 (50%)		Prairie plants, mainly grasses, 50% of roots in top 0.5 ft.
Costin et al (1964)	Aust. Snowy Mountains	2.0		Minor herbs, 1 ft. Perennial grasses, shrubs and trees, 2 ft. Forest areas, root penetration at least to depths of 8 ft , but 70-90% of roots in top 2 ft, mostly near surface.
Meinzer (1942, p. 263)	U.S.A.	3.0		The working depth of root systems seldom exceeds 6 ft and lies principally in the top 3 ft, for both herbaceous cover and trees.
Russell (1958, p. 426)				Root depths adjust to the rainfall distribution.
Donahue (1962, p. 324	U.S.A.			All plants adjust root depths to obtain 4" available water.

6.2 Evaporation from bare soil

Boughton (1965, p. 48) estimated the depth of roots on the catchments which he studied to be in the order of $2\frac{1}{2}$-3 ft. In his calculations for small catchments he used the values of upper and lower soil store capacities shown in Table 6.2. Using Boughton's store capacities and on assumed available water capacity of 2" per ft for the soil, root depths were estimated, and, as shown in Table 6.2, these depths were close to 3.4 ft.

Table 6.2: Estimation of root depths from parameter values used by Boughton (1965)

Catchment	USMAX pts	SSMAX pts	Total soil store capacity pts	Estimated root depth ft (total capacity ÷ 2" per ft AWC)
Scone	85	600	685	3.4
Badgerys Ck.	85	600	685	3.4
Wagga Wagga	60	600	660	3.3

However, the data in Table 6.1 indicate lower values for root depths on some catchments. When field measurements were made on the three New South Wales catchments, listed in Table 6.2, it was found that the catchment average root depths were considerably less than 3 ft, being as low as 7" for Wagga Wagga.

This suggested that although the values of SSMAX used by Boughton produced satisfactory results, they may not have been the values which occurred in nature (see Section 2.3). An an explanation it was conjectured that, on a catchment with shallow rooted vegetation, direct evaporation could possibly remove moisture from a depth well below the roots. If this was correct, then the lower soil zone depth would also extend to a greater depth than the roots. The literature on evaporation from bare soil was therefore surveyed to see if this hypothesis was feasible. The information obtained from the survey is summarised in Table 6.3 and indicates that, for bare soils at or below field capacity, the depth to which evaporation can remove moisture at a reasonable rate is in the order of 1 ft. Probably evaporation would occur from soil at a greater depth (1-3 ft), but at a very low rate. This indicated that the sum of the upper and lower soil store capacities on catchments with shallow rooted vegetation ($<$ 1 ft) would not exceed a figure in the order of 400 pts (2 ft x 2 in/ft AWC). Further discussion on this aspect is contained in Section 6.4.

Table 6.3: Evaporation from bare soil.

Source	Depth of penetration of evaporation from bare soil.
A.S.C.E. Hydrology Handbook (1949, p. 131)	Evaporation is effectively reduced by a crust of dry soil and below the upper 6-8" there is little loss of moisture by soil evaporation.
Alway & McDole (1917) quoted by Meinzer 1942, p. 379)	At moisture contents below field capacity the movement of moisture upwards from below 12" is very slow.
Rotmistrov (quoted by Meinzer 1942, p. 379)	Water which penetrates beyond 16-20" does not return to the soil surface except by way of plant roots.
Baver (1938, p.283)	Data by Veihmeyer (1927) and others have shown that evaporation losses are confined to fairly shallow depths.
Russell (1958, p.379)	Evaporation would not occur from below 3 ft and would probably be minor below about 8".
Chow (1964, p.6-18)	Surface evaporation can penetrate to a depth of 8-12".

6.3 Division between soil zones

In the model the upper soil zone is visualized as a very porous layer, situated above a denser subsoil. Soil in the upper zone will absorb rainfall regardless of the intensity until saturation is reached, then runoff commences, Boughton (1965, p.16-17). This would involve the establishment of positive soil moisture pressure in the upper soil zone, owing to a porosity change caused by textural or structural stratification (see Sections 2.3 and 7.1). The two criteria of a porous upper layer and the depth of change in porosity were employed to estimate the upper soil depth in the field on Scone, Wagga Wagga and Badgerys Ck. catchments.

6.4 Evaluation of zone depths

For the initial computer runs with the model, using data from Scone, Wagga Wagga and Badgerys Creek catchments, the soil zone depths were estimated by excavating holes on a grid over each catchment. The depth to the change in porosity was measured together with root depths. In most cases the upper zone was regarded as the zone of the dense grass roots and the mean depth of this zone over the catchment was adopted. For the above three catchments the upper zone depth was 2" to 3".

The model store capacities were initially estimated as follows:-

Upper soil store capacity (USMAX) - the product of the upper soil zone depth and the AWC estimated from Section 4.3.

Drainage store capacity (DSMAX) - the product of the upper soil zone depth and the NCP estimated from Section 5.1.3.

Lower soil store capacity (SSMAX) - the upper soil zone depth was subtracted from either the average root depth or two feet, whichever was the greater. The product of the resulting depth and the AWC of the soil was the estimated value of SSMAX. (Two feet was the estimated depth from which evaporation would remove soil moisture in the absence of roots, see Section 6.2).

The above estimation procedures gave satisfactory results for USMAX but not for DSMAX and SSMAX, and the latter two parameters will be further discussed.

Drainage store capacity

The values of DSMAX obtained from the product of the estimated NCP and upper soil depth did not produce good results. As described in Section 5.2 optimum values of DSMAX were later calculated for Scone, Wagga Wagga and Badgerys Creek catchments, by trial and error using the computer. A correlation was then established between DSMAX and a climate index.

For the test run on Parwan Weir catchment data, DSMAX was estimated from the "DSMAX Vs climate index" correlation, with descriptive catchment characteristics also being considered.

Lower soil store capacity

The results obtained by using an estimated lower soil store capacity in the order of 300-400 points for Scone catchment were irregular. Further trials for that catchment, with no upper limit on the capacity of the lower soil store, showed that the store could be filled to about 1000 points and then be almost emptied by evaporation. In addition, one parameter (lower soil store capacity) was thereby eliminated from the model and it became much easier to optimise the drainage store capacity and infiltration parameters. Application of the model to Wagga Wagga and Badgerys Creek catchments supported these conclusions.

The computer printout of the lower soil store value when runoff occurred showed the maximum values reached to be:-

Badgerys Creek	700 pts
Scone	1000 pts
Wagga Wagga	1380 pts

The recommended design procedure is that no limit be placed on the lower soil store capacity. For the calculation of evaporation loss from this store the ratio of existing store volume (SS) to maximum store capacity (SSMAX) is employed and for this purpose an average value of 1000 points was adopted for the pseudo-parameter designated by SSMAX in Chapter 10. This value of SSMAX operated in the evaporation loss calculations only and was not set as an upper limit on the amount of moisture which could be held in the lower soil store.

The question as to whether or not the "unlimited" values of SSMAX were the true values which occurred in nature, was not resolved. The measurement and analysis of soil moisture behaviour is considered the best avenue for further investigating this aspect.

7. INFILTRATION PARAMETERS

In the model, infiltration occurs into the lower soil store from the excess rainfall during runoff periods and each day from the drainage store until that store is empty. The daily rate of infiltration is governed by the amount of moisture in the lower soil store, and Boughton (1965) proposed a relationship between these two parameters which is illustrated in Fig. 26 and represented by the equation:-

$$F = F_c + (F_o - F_c)e^{-KS} \qquad \ldots\ldots \qquad (7.1)$$

where
- F = infiltration rate, pts/day
- Fc = minimum rate of infiltration, pts/day
- Fo = maximum rate of infiltration, pts/day
- S = amount of moisture in the lower soil store, pts (In the computer programme the symbol SS was used instead of S).
- K = additional parameter of the equation

Section 7.1 examines the infiltration portion of the model in relation to infiltration theory and the more complex soil profile structure which occurs in nature.

Next, in Section 7.2, the results of infiltration experiments were analysed to obtain information on the relationship between infiltration, soil texture and moisture content.

In Section 7.3 statistics were calculated from loss rate data and extended to daily values. This information indicated the general order of infiltration values for different types of soil and the section of the profile which should be associated with infiltration in the model.

The "daily infiltration Vs lower soil moisture level" curves were then derived (Section 7.4) by trial and error, using the results from computer runs with the model. The parameters in Boughton's infiltration equation were reduced from three to one, and this parameter was correlated with catchment slope (Section 7.5).

7.1 Infiltration theory

The fundamental concepts of moisture flow through unsaturated soils and the effects of textural and structural stratification have been built upon the work of Colman and Bodman (1944), Philip (1954, 1957, 1959), Miller and Gardner (1962), Horton and Hawkins (1964), Hanks (1965) and others.

The application of this theory to the model was discussed in Section 2.2. It was stated that wet front advance is retarded by soil stratification, causing positive pressure to be established in the upper soil, before infiltration proceeds into the lower soil under negative pressure. Generally, the division between the topsoil and transition soil would be the soil depth at which infiltration is first retarded.

A second important concept is that, in unsaturated soils, soil moisture suction increases as the pore size decreases. Consequently, infiltrating moisture is withheld from large pores, by small pores, to follow a downward flowpath through the small pores, Miller and Gardner (1962), Horton and Hawkins (1964). These conditions would tend to increase the importance of soil texture and decrease that of soil structure.

Summarily, the topsoil on a catchment acts as a buffer, producing positive pressure in the topsoil and runoff to begin, and a negative pressure regime with a small pore flowpath in the lower soil.

7.2 Experimental data

Data defining the penetration of moisture into soil may be accurately calculated on a digital computer for specific soil conditions and with known soil properties such as the soil suction and hydraulic conductivity versus moisture content relationships. This is a complex procedure and a limited amount of information has been determined by the approach. Preceding and supplementing this information are the results of physical experiments on moisture penetration.

An extensive search was made of both the theoretical and experimental sources for information which would enable "volume of penetration Vs time" relationships to be established. In some cases direct values were available and in others it was necessary to estimate data using infiltration and soil moisture theory.

The "infiltration volume Vs time" data are shown in Fig. 27. The log-log straight line relationships indicate that the data accords with the integral of the general form of Kostiakov's equation as follows:-

$$f = at^n \quad \ldots\ldots \quad \text{Kostiakov (1932)} \ldots \quad (7.2)$$

$$Q = \int at^n dt = \frac{a}{n+1} \cdot t^{n+1}$$

or $$Q = ct^b \quad \ldots\ldots \quad \ldots \quad (7.3)$$

or $$\log Q = \log c + b \log t \quad \ldots \quad (7.4)$$

The value of b varies from $\frac{1}{2}$ for dry soil to 1 for saturated soil, but c decreases with increasing initial wetness. The 24 hour volumes of infiltration vary fairly uniformly with soil texture, decreasing from sandy loam to light clay as indicated in Table 7.1. The representative values in this table were selected from Fig. 27. The decrease in infiltration with increasing initial soil moisture content may also be noted.

Table 7.1: Variation of infiltration with soil texture and moisture content

Texture	Initial moisture condition	24 hr volume of infiltration,pts
Sandy loam	dry field capacity	2100 1500
Light clay	dry wilting point field capacity saturated	220 175 87 47

The information in Fig. 27 and Table 7.1 indicates that, for the small Scone and Wagga Wagga catchments, the dry soil infiltration rates of 1000 and 350 pts/day determined by Boughton (1965) are associated with transition zone soil and not dense clay subsoil.

The "soil dry" infiltration data in Fig. 27 provided estimates of the order of magnitude of the parameter Fo in the infiltration equation, $F = F_c + (Fo - Fc)\ e^{-KS}$, for given soils. However the other remaining parameters of the equation could not be related to the data and it was necessary to investigate other avenues, as detailed in Sections 7.3 and 7.4.

7.3 Loss rates

The section describes an attempt to derive design infiltration parameter values by analysis of loss rate data. Statistics were calculated from the loss rates derived by Laurenson and Pilgrim (1963), to determine the extreme loss rates for catchment conditions of "wet in winter" and "dry in summer". It was intended to associate these statistical values with the parameters Fo and Fc in Boughton's infiltration equation:-

$$F = Fc + (Fo - Fc)\quad e^{-KS} \qquad \ldots\ldots \qquad (7.1)$$

The attempt was not successful in determining infiltration parameters for small catchments. However, the results could be of assistance in other research and the work will be described.

For each of the Laurenson and Pilgrim loss rates, an antecedent precipitation index (API) was calculated, using the equation:-

$$API = AP_1 + 0.69\ (AP_7 - AP_1) + 0.16\ (AP_{28} - AP_7) \ldots \quad (7.5)$$

where API = antecedent precipitation index
AP_1 = 1 day antecedent rainfall
AP_7 = 7 day antecedent rainfall
AP_{28} = 28 day antecedent rainfall

The equation is based on the regression:-

$$API_n = 0.9\ API_{n-1}$$

with 0.69 and 0.16 being the median coefficients for 2-7 days and 8-28 days respectively.

The loss rates were arranged into API classes and the relative frequency diagram is shown in Fig. 28. The median API is 1.373. An API less than 1.0 was classified as "catchment dry" and greater than 1.75 as "catchment wet". The months October- March were regarded as summer and April - September as winter. This classification was adopted in order to obtain reasonable sample sizes.

A sample of seven loss rates was obtained for "summer dry", with a median of 20 pts/hr, and this rate was derived using a time period of 2 hours. During the 2 hour period the total loss was therefore 40 pts.

For "winter wet" the sample comprised eleven loss rates, with a median of 6 pts/hr, derived using a time period of 1 hour. The total loss during the 1 hour period was therefore 6 points.

These values were extended to 24 hr rates, which is the time period used in operation of the model, as follows:-

Fig. 27 illustrates that the relationship between infiltration volume and time is logarithmic and in Section 7.2 a convenient equation was shown to be:-

$$Q = ct^b \quad \ldots\ldots\ldots \quad (7.3)$$

<u>or</u>

$$\log Q = \log c + b \log t \quad \ldots\ldots\ldots \quad (7.4)$$

where Q = volume of infiltration in t hours, pts.
t = time, hrs.
c = parameter dependent upon the particular soil and initial moisture content (for fixed conditions of infiltration)
b = $\frac{1}{2}$ to 1, depending upon the initial soil moisture content

The data in Fig. 27 show the exponent b to range from 0.5 (soil dry) to 1.0 (soil saturated). For a moisture condition of wilting point (catchment dry) a value of 0.6 was adopted, this being slightly greater than that for very dry soil (0.5). For a moisture condition of field capacity (catchment wet) a value of 0.75 was selected, as suggested by Krimgold and Beenhouwer (1954).

The equation, $Q = ct^b$, will plot as a straight line of slope b on log-log paper. If the slope (b) and one point on a line conforming to this equation are known, then the line can be readily drawn.

In Fig. 29 a line of slope 0.6 passes through the point representing the median "catchment dry" loss rate (2 hr, 40 pts) and extends to a 24 hr volume fo 180 pts.

Similarly, in the same figure, a line of slope 0.75 passing through the point representing the median "winter wet" loss rate (1 hr, 6 pts) indicates a 24 hr volume of 65 points.

It was initially postulated that, as Scone and Badgerys Creek catchments are both located in the podsol soil area, for which most of the Laurenson and Pilgrim loss rates were derived, the infiltration parameter values could be the same for the two catchments. Although the infiltration curves derived by Boughton (1965) differed for these two catchments, it was believed that this may have been owing to incorrect values for the related initial loss parameters.

For Scone and Badgerys Creek catchments, the "summer dry" rate of 180 pts/day was associated with the parameter Fo and the "winter wet" rate with the parameter Fc, in the infiltration equation, $F = Fc + (Fo - Fc) e^{-KS}$. The value of K was estimated from the date of Philip in Fig. 27, and the other model parameters from physical properties. The model was then operated on the computer for the two catchments.

The results were unsatisfactory. Infiltration curves were then derived from the computer printout and these curves resembled those determined by Boughton (1965). This derivation of the infiltration curves from computer results is described in detail in section 7.4. It was concluded that evaluation of the infiltration parameters from analysis of loss rate data was not successful and the research described in Section 7.4 was next pursued.

Two factors are believed to contribute to the non-applicability of the extended loss rate values to the infiltration parameters of the Boughton model.

Firstly, the loss rates were derived from catchments which have a median area of 620 sq ml. Catchments of that size may behave differently from the small Badgerys Creek and Scone catchments (15 and 40 acres), particularly as regards the initial loss and infiltration parameters of the Boughton model.

Secondly, the model of the rainfall - runoff process which was used for deriving the loss rates differed from the model proposed by Boughton, and this would create problems for the interchange of parameter values between the two models.

As an example of these effects the values of 180 pts/day (dry) and 87 pts/day (wet) calculated from loss rates are of the same order as the infiltration rates of 175 pts/day (wilting point) and 87 pts/day (field capacity) shown for light clay in Table 7.1. This indicates that the loss rate values represent losses into clay subsoil, whereas for application of the Boughton model to small catchments, the infiltration losses occur at least partly into the porous transition zone soil. This latter point is also discussed in Sections 2.2 and 7.7.

The similarity between the daily values calculated from loss rates, and the daily infiltration rates into clay, is the important finding in this section of the work.

7.4 Computer derivation of infiltration curves

The initial methods used to estimate the infiltration curves were not successful and a brief description only will be given. Although these estimates were used for the first computer run on each catchment, the trial and error method which was later used for estimating optimum curves produced convergence within a few trials, even if the first estimate was very inaccurate.

Upon failure of the curve parameter estimation from loss rate data

(Section 7.3) the next method consisted of inspecting the catchment soil profile and estimating the daily infiltration rate of the transition zone soil and clay subsoil from Table 5.11 (Section 5.1.3.2) and Fig. 27. Where one hour volumes of infiltration were estimated, these were extended to 24 hr values by using exponents of 0.6 (wilting point) and 0.75 (field capacity) in the equation:-

$$F_t = F_1 t^b \qquad \ldots\ldots \quad (7.6)$$

where F_t = infiltration volume in t hrs, pts.
F_1 = infiltration volume in 1 hr, pts.
t = time, hrs.
b = an exponent dependent upon the initial soil moisture content.

(This equation is apparent from inspection of Fig. 27 and was discussed in Section 7.3).

Various hypotheses were tried and discarded for estimating the lower soil store moisture capacity (Fig. 26). A similar course was followed when estimating the shape of the infiltration curve. It was found that any reasonable curve which commenced at a realistic value of Fo and became asymptotic to a value of F in the order of 15 pts, at a subsoil moisture level of about 1000 pts, was satisfactory for an initial estimate. As discussed in Section 6.4, the final procedure adopted was that no upper limit be placed on the lower soil store capacity.

The model's soil moisture and interception parameters were estimated from catchment inspection, while evaporation was estimated from Commonwealth Bureau of Meteorology monthly evaporation maps and monthly Penman factors, to convert pan evaporation to evapotranspiration. The Penman (1948) factors used were 0.6 for winter (May, June, July, August); 0.8 for summer (Nov, Dec, Jan, Feb) and 0.7 for autumn and spring. These estimates were considered satisfactory, with the exception of the drainage store capacity (DSMAX) which was later adjusted by trial and error.

The computer was programmed (Chapter 10) to print values of the model variables each time runoff occurred. An example of the printout is as follows:-

Date	Rainfall	Q	P	F	SS
7.12.64	140	15.86	82.4	90	327

where $Q = P - F \tanh(P/F)$

with Q = calculated runoff, pts
P = overflow from initial loss stores, pts
F = prevailing daily infiltration rate, pts/day
SS = lower soil store moisture level, pts
(or the value of S in the infiltration equation, $F = Fc + (Fo - Fc)e^{-KS}$).

This printout enabled a second estimate of the optimum infiltration curve to be determined as follows:-

Table 7.2 is part of a table listing values of Q for combinations of P and F in equation (7.7). Entering this table at the printout value of P, the value of F was determined which would have produced the recorded runoff. This value of F and the printout value of SS were then plotted as a point, as shown in Figs. 30 - 32.

The procedure was repreated for each incorrectly calculated runoff event. The values of F and SS for correctly calculated runoff events were also plotted. The estimated and recorded runoff values were entered against each plotted point, and, taking these values into account, a second estimated infiltration curve was drawn.

Table 7.2: Values of Q(pts) for combinations of P and F in the equation $Q = P - F \tanh(P/F)$

		F, pts/day				
		10	20	30	40	50
P, pts	5	0.37	0.10	0.04	0.02	0.01
	10	2.38	0.75	0.35	0.20	0.13
	15	5.94	2.29	1.13	0.66	0.43
	20	10.35	4.76	2.51	1.51	1.00
	25	15.13	8.03	4.53	2.81	1.89
	30	20.04	11.89	7.15	4.59	3.14
	35	25.01	16.17	10.30	6.84	4.78
	40	30.00	20.71	13.89	9.53	6.79
	45	35.00	25.43	17.84	12.62	9.18
	50	40.00	30.26	22.06	16.06	11.92
	55	45.00	35.16	26.49	19.80	14.97
	60	50.00	40.09	31.07	23.79	18.31
	65	55.00	45.06	35.77	27.98	21.91
	70	60.00	50.03	40.55	32.34	25.73

Table 7.2 (cont'd.) Values of Q (pts) for combinations of P and F in the equation $Q = P - F \tanh (P/F)$

		F, pts/day				
		10	20	30	40	50
P, pts	75	65.00	55.02	45.40	36.83	29.74
	80	70.00	60.01	50.28	41.43	33.91
	85	75.00	65.00	55.20	46.12	38.22
	90	80.00	70.00	60.14	50.87	42.65
	95	85.00	75.00	65.10	55.68	47.18
	100	90.00	80.00	70.07	60.53	51.79

The plotted points became relatively stable after two or three estimation cycles. The drainage store parameter (DSMAX) was optimised, as described in Section 5.3, and a final infiltration curve then estimated as shown in Figs. 30 - 32.

7.5 Reduction of infiltration parameters

The derived infiltration curves were close to those obtained by Boughton (1965), although different values were used for the other parameters in the model.

With the exception of Wagga Wagga catchment, Boughton's curves were adopted. For Wagga Wagga the curve in Fig. 30 was a better fit to the derived points and was therefore selected. To increase the sample size, Boughton's curves for South Creek and Eastern Creek were included and the equations for the complete set of infiltration curves were:-

Scone	$F = 15 + (1000 - 15)e^{-0.0068S}$	......	(7.8)
Wagga Wagga	$F = 10 + (510 - 10)\ e^{-0.006S}$	......	(7.9)
Badgerys Creek	$F = 25 + (225 - 25)\ e^{-0.005S}$	......	(7.10)
Eastern Creek	$F = 5 + (200 - 5)\ e^{-0.005S}$	......	(7.11)
South Creek	$F = 10 + (110 - 10)\ e^{-0.005S}$	......	(7.12)

The curves are illustrated in Fig. 33.

The infiltration equation, $F = Fc + (Fo - Fc)\ e^{-KS}$, has three parameters and it was considered desirable that these be reduced. The following account describes how the reduction was achieved.

The equations were plotted on semi-log paper in the form "(F-Fc) Vs S" as shown in Fig. 34. Inspection of Figs. 33 and 34 indicated that the point (S=800, F=14) could be made common to all the curves without significant loss in accuracy. A constant value of 10 was adopted for Fc, reducing the number of parameters from three to two.

The point (800, 4) was selected to be made a common point for all curves, on a semi-log plot of "(F - 10) Vs S". The number of parameters was thus reduced to one, this being the slope of the line passing through the point (800, 4), or pairs of values for Fo and K.

The relationship between Fo and K is illustrated in Fig. 36. This was determined using Table 7.3 which lists values of e^{-KS} for combinations of K and S. For a semi-log plot of the infiltration equation in the form "(F-10) Vs (Fo-10)e^{-KS}", as in Fig. 35, the value of Fo for a line of slope (K), passing through the point (800, 4), is obtained as in the following example:-

For $K = 0.005$;

$e^{-K \times 800} = 0.018$ .....(from Table 7.3)

$(Fo-10) \times 0.018 = 4$ .....(for the line to pass through (800, 4))

$\therefore Fo = 232$

The procedure was repeated for a range of K values to obtain the curve in Fig. 36.

By trial and error, using Table 7.3, curves were determined of close fit to the original infiltration equations (7.8 to 7.12), with Fc equal to 10 and passing through the point (800, 4), on a semi-log plot (Fig. 34) of "(F-10) Vs S". These curves are shown in semi-log form in Fig. 35 and on arithmetic scales in Fig. 37.

The equations of the curves are:-

Scone	$F = 10 + (1000 - 10)e^{-0.0068S}$	.... (7.13)
Wagga Wagga	$F = 10 + (510 - 10)e^{-0.006S}$	.... (7.14)
Badgerys Creek	$F = 10 + (232 - 10)\ e^{-0.005S}$	.... (7.15)
Eastern Creek	$F = 10 + (188 - 10)\ e^{-0.0047S}$	.... (7.16)
South Creek	$F = 10 + (95 - 10)\ e^{-0.0038S}$	.... (7.17)

7.6 Correlation of infiltration with catchment slope

An examination of the catchment physical properties and the infiltration curves indicated that catchment slope was a significant factor and infiltration was therefore correlated with this parameter.

Table 7.3: Values of y in the equation: $y = e^{-KS}$

K	S: 100	200	300	400	500	600	700	800	900	1000
.0010	0.904	0.818	0.740	0.670	0.606	0.548	0.496	0.449	0.406	0.367
.0012	0.886	0.786	0.697	0.618	0.548	0.486	0.431	0.383	0.339	0.301
.0014	0.869	0.755	0.657	0.571	0.496	0.431	0.375	0.326	0.283	0.246
.0016	0.852	0.726	0.618	0.527	0.449	0.382	0.326	0.278	0.236	0.201
.0018	0.835	0.697	0.582	0.486	0.406	0.339	0.283	0.236	0.197	0.165
.0020	0.818	0.670	0.548	0.449	0.367	0.301	0.246	0.201	0.165	0.135
.0022	0.802	0.644	0.516	0.414	0.332	0.267	0.214	0.172	0.138	0.110
.0024	0.786	0.618	0.486	0.382	0.301	0.236	0.186	0.146	0.115	0.090
.0026	0.771	0.594	0.458	0.353	0.272	0.210	0.162	0.124	0.096	0.074
.0028	0.755	0.571	0.431	0.326	0.246	0.186	0.140	0.106	0.080	0.060
.0030	0.740	0.548	0.406	0.301	0.223	0.165	0.122	0.090	0.067	0.049
.0032	0.726	0.527	0.382	0.278	0.201	0.146	0.106	0.077	0.056	0.040
.0034	0.712	0.506	0.360	0.257	0.182	0.130	0.092	0.065	0.046	0.033
.0036	0.697	0.486	0.339	0.236	0.165	0.115	0.080	0.056	0.039	0.027
.0038	0.683	0.467	0.319	0.218	0.149	0.102	0.069	0.047	0.032	0.022
.0040	0.670	0.449	0.301	0.201	0.135	0.090	0.060	0.040	0.027	0.018
.0042	0.657	0.431	0.283	0.186	0.122	0.080	0.052	0.034	0.022	0.014
.0044	0.644	0.414	0.267	0.172	0.110	0.071	0.045	0.029	0.019	0.012
.0046	0.631	0.398	0.251	0.158	0.100	0.063	0.039	0.025	0.015	0.010
.0048	0.618	0.382	0.236	0.146	0.090	0.056	0.034	0.021	0.013	0.008
.0050	0.606	0.367	0.223	0.135	0.082	0.049	0.030	0.018	0.011	0.006
.0052	0.594	0.353	0.210	0.124	0.074	0.044	0.026	0.015	0.009	0.005
.0054	0.582	0.339	0.197	0.115	0.067	0.039	0.022	0.013	0.007	0.004
.0056	0.571	0.326	0.186	0.106	0.060	0.034	0.019	0.011	0.006	0.003
.0058	0.559	0.313	0.175	0.098	0.055	0.030	0.017	0.009	0.005	0.003
.0060	0.548	0.301	0.165	0.090	0.049	0.027	0.014	0.008	0.004	0.002
.0062	0.537	0.289	0.155	0.083	0.045	0.024	0.013	0.007	0.003	0.002
.0064	0.527	0.278	0.146	0.077	0.040	0.021	0.011	0.005	0.003	0.001
.0066	0.516	0.267	0.138	0.071	0.036	0.019	0.009	0.005	0.002	0.001
.0068	0.506	0.256	0.130	0.065	0.033	0.016	0.008	0.004	0.002	0.001
.0070	0.496	0.246	0.122	0.060	0.030	0.014	0.007	0.003	0.001	0.000
.0072	0.486	0.236	0.115	0.056	0.027	0.013	0.006	0.003	0.001	0.000
.0074	0.477	0.227	0.108	0.051	0.024	0.011	0.005	0.002	0.001	0.000
.0076	0.467	0.218	0.102	0.047	0.022	0.010	0.004	0.002	0.001	0.000
.0078	0.458	0.210	0.096	0.044	0.020	0.009	0.004	0.001	0.000	0.000
.0080	0.449	0.201	0.090	0.040	0.018	0.008	0.003	0.001	0.000	0.000
.0082	0.440	0.193	0.085	0.037	0.016	0.007	0.003	0.001	0.000	0.000
.0084	0.431	0.186	0.080	0.034	0.014	0.006	0.002	0.001	0.000	0.000
.0086	0.423	0.179	0.075	0.032	0.013	0.005	0.002	0.001	0.000	0.000
.0088	0.414	0.172	0.071	0.029	0.012	0.005	0.002	0.000	0.000	0.000
.0090	0.406	0.165	0.067	0.027	0.011	0.004	0.001	0.000	0.000	0.000
.0092	0.398	0.158	0.063	0.025	0.010	0.004	0.001	0.000	0.000	0.000
.0094	0.390	0.152	0.059	0.023	0.009	0.003	0.001	0.000	0.000	0.000
.0096	0.382	0.146	0.056	0.021	0.008	0.003	0.001	0.000	0.000	0.000
.0098	0.375	0.140	0.052	0.019	0.007	0.002	0.001	0.000	0.000	0.000
.0100	0.367	0.135	0.049	0.018	0.006	0.002	0.000	0.000	0.000	0.000

The overland slope ($\mathscr{S}$, %) for each catchment was estimated from equation (7.18) by placing a square grid on a contour map of the catchment, of contour interval (X, ft) and determining the number of grid intersections with contour lines (N) and the length of grid lines within the catchment (L, ft).

$$\mathscr{S} = \frac{157 \times I \times N}{L}, \% \qquad \ldots\ldots \qquad (7.18)$$

The estimated catchment slopes were:

Catchment	Slope, %
Scone	18.6
Wagga Wagga	12.4
Badgerys Creek	5.62
Eastern Creek	4.84
South Creek	4.78

"Catchment slope Vs Fo" was plotted and a least square parabola fitted to the points. The equation of the parabola was:-

$$Fo = 61.1 + 10.30\mathscr{S} + 2.15\mathscr{S}^2 \qquad \ldots\ldots \qquad (7.19)$$

with a coefficient of correlation of 0.98 and accounting for 96.8% of the variance. The relationship is shown in Fig. 38.

It should be remembered that the infiltration portion of the model is designed to simulate percolation from the topsoil into the transition soil and subsoil. The model component does not simulate infiltration into the topsoil, which may proceed at an unlimited rate in the model.

The correlation between infiltration and slope represents the subsurface downhill flow of moisture, mainly through the transition zone soil, over a catchment. The moisture may by-pass an instrument installed to measure runoff from a catchment and/or pond in the soil around the lowest point, to be evaporated at a high rate.

This phenomenon is apparent on many catchments on the Great Dividing Range, particularly on the north coast of New South Wales. Areas where the moisture is concentrated and appears at the ground surface are termed "springs" or "seepage areas" and are frequently indicated by a prolific growth of tall grass.

The above drainage process is discussed by McDonald (1967) who also points out the resultant tendency toward xerophytic vegetation on the upper reaches of a catchment, while lush and mesophytic vegetation exist on the lower reaches. He describes a field experiment on a catchment of 8% slope, where it was shown that applied moisture flowed downhill quite rapidly within the surface soil layers and above the clay subsoil.

Further, Hewlett and Hibbert (1963) investigated the drainage of sloping soils and concluded that, in steep terrain, unsaturated subsurface drainage is also of significant magnitude and suggested slope as a factor affecting the process.

It should be appreciated that the correlation in Fig. 38 is based on a small sample and a larger sample would probably have greater variance.

7.7 Applications of the infiltration hypothesis

The correlation between infiltration and slope and the indicated magnitude of subsurface flow suggest two important possibilities.

Firstly, it should be possible to increase catchment yield by construction of a circumventing drain penetrating into dense subsoil. This effect would increase with increasing catchment slope.

Secondly, variations in subsurface drainage geometry may be responsible for apparently identical catchments which show marked differences in runoff. For example, the twin S.C.S. catchments at Scone, which were reported by Boughton (1965, p. 62) as having nearly identical appearance but with significant differences in the runoff records.

7.8 Design procedure

On small catchments the transition zone soil should be considered as part of the soil profile which governs the infiltration section of the model. The daily infiltration parameters have been correlated with catchment overland slope and the "catchment dry" infiltration parameter (Fo) increases with increasing slope.

To obtain the infiltration curve for a catchment, the catchment overland slope should be determined by the grid-contour intersection method, Fo estimated from Fig. 38, K (which was made a function of Fo) determined from Fig. 36 and these values entered in the equation,

$$F = 10 + (Fo - 10)e^{-KS}.$$

8. CATCHMENT AREA EFFECT

Although the problem of increased runoff loss with increasing catchment area is ancillary in this project, the investigations on soil moisture behaviour irradiated the subject and a further brief examination was pursued.

Boughton (1965) used the term "transmission loss" to describe the effect. This phrase usually refers to loss into the bed and banks of a main stream, whereas Boughton (p. 77) also associates it with an integrated infiltration loss over a catchment. Because of the uncertainty of definition the term "area effect" seemed more suitable and was adopted.

It was considered that large and small catchments differ mainly in that the former have a system of small channels, a length of main stream and require considerable time for runoff to reach the outlet, whereas, for the latter, runoff is primarily by overland flow (no system of small channels) and occupies a relatively short period of time.

For his model, Boughton considered these differences to produce a trend of increasing initial loss with increasing catchment area and the volume of water involved was as high as 400 pts (South Creek catchment). The question arises as to which physical part of a catchment accommodates the volume of water assigned to the effect.

The following three catchment components will be examined as possible storages for the water:-

(i) Clay subsoil.
(ii) Transition zone soil.
(iii) Banks and bed of the main stream.

8.1 Clay subsoil

The analysis of loss rates and soil moisture data in Section 7 showed that the expected maximum rates of infiltration into clay subsoil were approximately 180 pts/day (catchment dry) and 80 pts/day (catchment wet). This indicates that the capacity of 400 pts attributed to area effect and assigned to the initial loss store, would not occur into clay subsoil.

To support this point a further analysis was made using loss rates, which the calculations in Section 7.2 indicated to represent infiltration into clay subsoil. It was conjectured that, if the area effect loss occurred into clay subsoil, then the loss would be included as a component in derived loss rates. If this were the case, then loss rates could also be expected to increase with increasing catchment area.

The hypothesis was examined by correlating the estimated "median catchment loss rate" with "catchment area, using the data of Laurenson and Pilgrim (1963) and Karoly (1965). The data are listed in Table 8.1 and the correlation is shown in Fig. 39.

Table 8.1: Catchment area and median loss rate

Catchment area, sq ml	Estimated median loss rate in/hr
9000	0.100
775	0.185
640	0.130
2200	0.120
4050	0.040
5350	0.075
1520	0.200
1720	0.130
810	0.040
3100	0.045
9.6	0.185
0.27	0.125
34.6	0.070
3383	0.120
606	0.125
740	0.070
290	0.090
245	0.020
16.3	0.080
26.8	0.090
3345	0.060
338	0.130
258	0.145
17,800	0.030
0.331	0.090
1.60	0.220
3.40	0.100
33	0.180

The coefficient of correlation was -0.32 and Student's t test indicated the correlation to be significant at the 5% level (i.e. the hypothesis Ho: $\rho = 0$, was rejected by a one tailed test, with 5% probability of a Type I error).

The correlation revealed a decrease in loss rate with increasing catchment area, which is the opposite to that expected if the "area effect" produces an increased loss into clay subsoil. However, the negative correlation is not conclusive as it is probably owing at least partly to the non-uniformity of rainfall on large catchments tending to decrease the derived loss rates.

8.2 Transition soil

The soil moisture data in Section 8 indicate that porous transition zone soil would be capable of accommodating the moisture assigned by Boughton to transmission loss (or area effect). The increased time of runoff and the effect of water head in the small channel system on large catchments, would be sufficient for at least part of the transition soil to become saturated and produce an apparent increase in initial loss for the Boughton model.

However, there are two other points which should be considered before any conclusions are proposed:

(i) In Boughton's model, the initial loss and infiltration parameters are inter-related and, also, consideration of the infiltration equations (7.13 to 7.17) reveals a definite trend for the infiltration parameter (Fo) to decrease with increasing catchment area. An increased initial loss could therefore be compensated by a lower infiltration curve.

(ii) Bell (1966, Ch.5) correlated mean annual rainfall with mean annual runoff for a sample of 23 N.S.W. catchments which varied in area from 6 to 3000 sq ml. There was no bias in the correlation which could be attributed to catchment area. This indicated that there was no increase in total catchment loss with increasing area, for these catchments.

For increasing catchment area an increase in the depth of saturation into the transition soil and then, over a period of time, the drainage of water downhill through the transition soil (see Section 7.5) to finally appear in the main stream, would accord with all of the foregoing evidence.

This is considered a likely explanation of the area effect. It would not involve the great increase in losses indicated by Boughton (and not found by Bell), but would produce less surface runoff and increased base flow.

The possibility of overestimating base flow and thereby underestimating individual runoff events was suggested by Bell (Univ. of N.S.W. - personal communication). The consequent comparison of estimated and recorded flows by summation of individual events could lead to error. This may be overcome by basing the comparison of runoff for large catchments on annual streamflow, as well as on the sum of individual events.

8.3 Main stream

The values for losses from the main stream, quoted by Boughton (1965, p.77) ex Keppel and Renard (1962), Laurenson (1962) and Sharp and Saxton (1962), indicate that the main stream channels on large inland catchments could cause considerable water losses. However, if large transmission losses occur in eastern N.S.W. streams, and the loss increases with catchment area, then it is surprising that this was not apparent in the analysis of Bell (1966).

Further research on this aspect was not pursued.

8.4 Summary

The increase in initial loss with increasing catchment area, noted by Boughton, could be attributed to either infiltration into the transition zone soil (i.e. inclusion of part of the transition zone soil in the upper soil zone), losses from the main stream, or both.

Care should be exercised to ensure that the water allocated to this loss is not just temporarily delayed in storage, to appear in the stream channel at a later date. This may be checked by comparing the estimated and recorded annual catchment yield.

Because of the area effect, the methods adopted in this project for evaluating the model parameters would not be suitable for application to large catchments, without amendment.

9. INTERCEPTION STORE CAPACITY

In Boughton's model, the interception store capacity represents the amount of rainfall intercepted and held on the surface of vegetation, then later depleted by evaporation.

Section 9.1 contains a theoretical discussion of interception loss. In Section 9.2, values of the store capacity, determined by four different methods, are presented and followed by a summary. Finally, design values are listed for use in application of the model (Section 9.3).

9.1 Components of interception loss

The components of interception loss to vegetation are indicated in Fig. 40 and may be presented mathematically by the equation

$$I = V + \alpha t$$

or	interception loss	=	water film stored on the surface of vegetation	+	evaporation loss from the surface of vegetation during the storm.

The storage component (V) is the capacity of the interception store in the model.

The evaporation component (αt) is provided for by the operating rule of the model, that evaporation proceed at a high rate after a storm.

The following points should be kept in mind when evaluating interception loss data:-

(i) The general accuracy of the model.
(ii) The accuracy of measurements in interception studies.
(iii) Increased evaporation from the wet surface of vegetation is accompanied by a decrease in moisture removal by plant roots (Chow, 1964, p. 6-9).
(iv) The variability of interception loss and its dependence on climatic conditions such as wind velocity, during a storm.

9.2 Evaluation of V

The sources from which data were extracted for the parameter V were divided into the following four groups:-

(i) Field studies of interception losses.
(ii) Theoretical calculations based on wetted surface area.
(iii) Laboratory measurements of the moisture retained by sprinkled vegetation.
(iv) General range of values quoted in the literature.

Data from the four groups will be presented and then evaluated in a summary.

9.2.1 Field studies

Table 9.1 lists values of V determined from field studies, by fitting a regression equation of the form $I = V + \alpha t$ to observed interception data.

Table 9.1: Values of V from field studies

Source	Cover	Interception storage, V	
		Remarks	Value, pts
Horton (1919)	Trees	Range Median	1.5 - 6.0 3.5
	Grown crops	Approaches that of trees	3.0 - 3.5
	Grass	.00005 x height (ft) for height of 2 ft.	1.0
Johnson (1942) ex Kittredge (1948, p. 103)	Young ponderosa pine	Two stands	4.0 2.0
Rowe (1941) ex Kittredge (1948, p. 103)	Brush type, oak and buckeye		2.0
Niederhof & Wilm (1943) ex Kittredge (1948, p. 103)	Lodgepole pine	382 trees/acre 206 " " 147 " "	2.9 0.7 1.5
Clark O.R. (1940) ex Kittredge (1948, p. 112)	Grass, big bluestem		2.0

9.2.2 Theoretical calculations

The value of (V) may be estimated by calculations based on the surface area of vegetation and the film thickness of retained moisture, or from the amount of moisture retained per leaf of foliage. Table 9.2 summarises values obtained from this approach.

Table 9.2: Values of V from theoretical calculations

Source	Cover	Interception storage, V: Remarks	Interception storage, V: Value, pts
Horton (1919)	Trees, oak	500,000 leaves/tree of 40 ft crown dia., 20 drops of water per leaf, of av. dia. 1/8".	5.6
	Crop, rye	3,000 stalks/acre, 120 drops of water/stalk, average drop dia. $\frac{1}{2}$" (does not include storage in heads).	4.7
		Value of t	
Merriam (1961) ex Penman (1963, p. 20)	Rye grass	.005 in t = av. water film thickness over surface (upper & lower) of vegetation.	
	Blue grass	.008 in	
	Monterey pine	.003 in	
		Value of R; R = leaf surface / ground area	
Steiger (1930)	Big bluestem	6	3.6
	Big bluestem, mixed with other grasses.	3	1.8
	Blue grama grass	2.5	1.5
Flory (1936)	Little bluestem & other plants	20 V calculated from V = Rt, with t = .006 in	12.0
Clark (1940)	Slough grass	9	5.4
	Big bluestem, exclusive of other species in the area.	12.5	7.5

9.2.3 Laboratory measurements

With this approach vegetative cover is removed from a small area in the field, say 1 sq ft, and subjected to artificial rainfall in the laboratory.

The value of V is obtained by a weighing procedure. The relevant data are presented in Table 9.3.

Table 9.3: Values of V from laboratory measurement

Source	Cover	Interception storage, V	
		Remarks	Value pts
Clark (1940)	Mat forming types:	Vegetation taken from 1 sq. ft, sprinkled & weighed. Values converted from gm/sq ft to ins depth by factor 0.043	
	Slough grass		3.3
	Puncture vine		3.2
	Knot weed		3.0 median 3.0
	Spotted spurge		2.2
	Prostrate pigweed		2.0
	Erect types:		
	Prairie sage		11.1
	Stink grass		9.7
	Big blue stem (dense, 2' high)		9.2
	Psoralea, big blue		9.4
	stem and bluegrass		9.1
	Tall goldenrod		7.1
	Saltbush		7.7
	White sweetclover		7.2
	Buffalo grass		6.5 median 6.85
	Burning bush		6.3
	Tall panic grass		6.3
	Prairie dropseed		5.9
	Bindweed		5.8
	Foxtail		5.8
	Purslane		4.6
Grah & Wilson (1944)	Monterey pine	Branches suspended from balance and sprayed at 0.7 in/hr until saturated.	5.3
	Baccharis pilularis		3.3
Burgy & Pomeroy (1958)	Grass, tall pescue and soft chess about 10" high, cover density close to 100%.	Field conditions closely simulated and all interception loss components evaluated.	4.1 - 4.8

Table 9.3 (cont'd.) Values of V from laboratory measurements

Source	Cover	Interception storage, V Remarks	Value pts Wet	Wet & shaken
Beard (1956)	Mature veld of following species & height:-	Grass cut from 1 sq ft stood upright in wire bucket and sprinkled. Retained moisture determined by weight difference. Grass shaken and re-weighed (to simulate effect of wind).		
	Cymbopogan sp. - 9.5ft		24	11
	Themeda triandra - 3 ft		9	5
	Hyparrhenia - 5 ft		6	3
	Mixed veld unburnt for 3 yrs 2-4 ft		10	5
	Aristida junciformis 2.5 ft		9	3
	Kikuyu (mat) 0.5 ft		11	7

9.2.4 General range of V

Various reviewers have quoted a general range for the value of V and this information is summarised in Table 9.4.

Table 9.4: General range of V

Source	Interception storage, pts Remarks	Range of V, pts
Chow (1964, p.6-9)	Range of (V) in interception equation, $I = V + \alpha t$, for any one storm	1.0 - 5.0
Kittredge (1948)	Interception storage per shower	2.0 - 10.0
Bell (1963)	Literature survey	3.0 - 10.0

9.2.5 Summary

Consideration of the above data leads to the following deductions with regard to values of interception and storage capacity:-

(i) Values obtained by fitting the equation, $I = V + \alpha t$, to field data are generally lower than values from laboratory measurements and theoretical calculations.

(ii) This difference could be owing to the effects of wind which reduces the value of (V) and increases the term (α t), or to the difficulties inherent in the field measurement of small quantities of moisture.

(iii) The expected range of (V) is 1 - 10 pts. Within this range the selection of design values could be guided by theoretical considerations, but is largely arbitrary. Estimated values of (V) from each source were assembled in Table 9.5 and medians calculated for various types of cover. However, a consistent difference in storage capacity for trees, crops and grass of various heights was not evident.

Table 9.5: Estimated values of V (pts) for tree, grass and crop cover

Source	Cover				
	Trees	Grass			Crops
		2 ft.	2-6 ft.	6 ft.	
Horton (field	3.5	1.0	2.0	4.0	3.2
Johnson (field)	3.0				
Rowe (field)	2.0				
Niederhof & Wilm (field)	2.9				
Clark ex Kittredge (field)			2.0		
Horton (theoret.)	5.6				4.7
Penman-Steiger (theoret.)			1.8) 1.5) 1.6	3.6	
- Flory (theoret.)	12.0				
- Clark (theoret.)	5.4			7.5	
Clark (lab.)	3.0		6.9		
Grah & Wilson (lab.)	4.3				
Burgy & Pomeroy (lab.)		4.5			
Beard (lab.)		7.0	5) 5) 3) 3) 4.0	24) 11) 17	
Median	3.25	4.95	2.0	5.75	3.85

9.3 Design values

The interception storage component (V) which is the interception store capacity (VSMAX) in the model, is difficult to measure accurately and the available data have considerable variance. The points stated in Section 9.1 regarding the accuracy of the model, the accuracy of interception measurements and anomalies which are inherent in interception studies, should be remembered when considering interception data.

For trees, crops and grass the interception store capacity (VSMAX) may vary within the range 1-10 pts and 5 pts is a reasonable estimate for grassed catchments for which there is no secondary interception. A value of 10 pts could be estimated on theoretical bases for circumstances such as two layer vegetation, for example a forest with appreciable grass.

The linear variation of interception store capacity, with "percent of vegetal cover", listed in Table 9.6, was adopted for the grassed catchments with which this project is concerned. The "percent vegetal cover" is defined as the percentage of the total catchment area covered by vegetation.

This table was prepared by considering the collected data as a whole and is therefore partly subjective. The table should provide a better estimate of VSMAX than the general value of 15 pts adopted by Boughton (1965), or the values listed by Crawford and Linsley (1966), for the interception store capacity of the Stanford Watershed Model, of 10, 15 and 20 pts for grassland, moderate forest and heavy forest respectively.

Table 9.6: Design values of interception store capacity (VSMAX) for grassed catchments

% Vegetal cover	Interception store capacity, pts
100 - 80	5
80 - 60	4
60 - 40	3
40 - 20	2
20	1

The maximum probable error in the value of VSMAX estimated from Table 9.6 is 2 or 3 pts, which is approximately 3% of the total initial loss capacity (i.e. the sum of the interception, upper soil and drainage store capacities). This order of accuracy is considered acceptable for the estimation of the model parameters.

10. COMPUTER PROGRAMME FOR MODEL OPERATION

The structure and operation of the Boughton model have been described in Section 2.1. The calculations were programmed in PL1 language and run on the University's IBM 360/50 computer.

A listing of the programme is presented in Table 10.1 and the variable names are listed and explained in Table 10.2.

A flow chart showing the various sections of the calculations is presented in Fig. 41. The operations designated by A, B, C .. J in this figure are explained in Table 10.3.

10.1 Input

The input data are read into the computer in the following order:

Evaporation

E(I)	Twelve monthly values, representing the average daily rate of potential evaporation, in units of pts/day, for each month of the year.

Rainfall

DTA(J, I, K)	The daily rainfall values, in units of points, were arranged into a (31 x 12 x No. of yrs) array. For months with less than 31 days, the figure (-1) was used to fill the blank spaces of the array. When this figure was encountered the calculations were by-passed and the next rainfall data item selected.

Catchment parameters

VSMAX	The capacity of the interception store, pts.
VS	Volume of moisture in the interception store, pts.
DSMAX	The capacity of the drainage store, pts.
DS	Volume of moisture in the drainage store, pts.
USMAX	The capacity of the upper soil store, pts.
US	Volume of moisture in the upper soil store, pts.
SSMAX	The pseudo-parameter for the lower soil store capacity, pts. This parameter was used in evaporation calculations only and was not set as the upper limit of the lower soil store. (See also Section 6.4).

Table 10.1: Computer Programme for the Boughton Model.

```
YIELD:  PROCEDURE OPTIONS (MAIN);
 M=55; N=66; BEGIN;
  DECLARE (DTA(31,12,M:N)) FIXED;
  DECLARE RFALL FIXED DEC (4,1);
  DECLARE (DSMAX) FIXED;
   DECLARE EVAP(12) FIXED DEC (4,2);
     DO  I= 1 TO 12;
      GET LIST (EVAP(I));
     PUT SKIP; PUT LIST (I,   .I));
     END;
 EDITT: PUT PAGE; PUT EDIT('DATE','RFALL','Q','P','F','SS')
                          (COLUMN(4),A(4),COLUMN(14),A(5),COLUMN(26),A(1),
                           COLUMN(36),A(1),COLUMN(45),A(1),COLUMN(53),A(2));
  FEEDD: DO K=M TO N; DO I=1 TO 12; DO J=1 TO 31;
            GET LIST (DTA(J,I,K));
          END; END; END;
       DSMAX=35.0;
VS=0.0; VSMAX=3.0; US=16.5; USMAX=33.0; SSMAX=1000.0; DS=0.0;
SS=SSMAX/2; SIGQ=0.0; F=10+(426-10)*(2.71828**(-0.0058*SS));
  LOOPE: DO K=M TO N; DO I=1 TO 12; DO J=1 TO 31;
            RFALL=DTA(J,I,K);
  BLANKS: IF RFALL=-1
            THEN GO TO ENDDAY;
  DAILY: IF RFALL=0
             THEN GO TO NORAIN;
             ELSE GO TO RAIN;
  RAIN:      VS=VS+RFALL;                                   /* REPLENISH STORES */
          IF VS>VSMAX
             THEN DO; US=US+(VS-VSMAX);
                      VS=VSMAX; END;
             ELSE VS=VS;
          IF US>USMAX
             THEN DO; DS=DS+(US-USMAX);
                      US=USMAX; END;
             ELSE DS=DS;
          IF DS>DSMAX                                        /* CALCULATE RUNOFF */
             THEN DO; P=DS-DSMAX;
                      DS=DSMAX;
                      Q=P-(F*(TANH(P/F))); END;
             ELSE DO; P=0;
                      Q=0; END;
          IF Q>0
             THEN DO; SIGQ=SIGQ+Q;
                                                                     /* PRINT */
                      PUT EDIT(J,I,K,RFALL,Q,P,F,SS)
                            (SKIP(2),COLUMN(2),F(2),COLUMN(5),F(2),
                             COLUMN(8),F(2),COLUMN(15),F(3),COLUMN(22),F(8,5),
                                COLUMN(34),F(5,1),COLUMN(42),F(6,1),
                             COLUMN(52),F(6,1));
                 END;
            E=EVAP(I);                                       /* EVAPN LOSSES */
         IF VS<E
           THEN DO; US=US-(E-VS)/2;
                    SS=SS-(E-VS)/2;
                    VS=0; END;
           ELSE DO; VS=VS-E;
                    US=US;
```

(cont'd. over)

Table 10.1 (cont'd.)

```
                    SS=SS; END;
        IF (P-Q)>0                                        /* INFILTRN DS TO SS */
           THEN IF F<DS+(P-Q)
              THEN DO; SS=SS+F;
                       DS=DS-(F-(P-Q)); END;
              ELSE DO; SS=SS+DS+(P-Q);
                       DS=0; END;
        IF (P-Q)=0
           THEN IF F>=DS
              THEN DO; SS=SS+DS;
                       DS=0; END;
              ELSE DO; SS=SS+F;
                       DS=DS-F; END;
           F=10+(426-10)*(2.71828**(-0.0058*SS));                /* CALC NEW F */
           GO TO ENDDAY;
NORAIN: IF VS=0          /* VS EMPTY EVAPN FROM US */      /* EVAPN LOSSES */
          THEN IF EVAP(I)>35*(US/USMAX)
                  THEN DO; E=35*(US/USMAX);
                           US=US-E/2; END;
                  ELSE DO; E=EVAP(I);
                           US=US-E/2; END;
        IF VS=0          /* VS EMPTY EVAPN FROM SS */
          THEN IF EVAP(I)>35*(SS/SSMAX)
                  THEN DO; E=35*(SS/SSMAX);
                           SS=SS-E/2; END;
                  ELSE DO; E=EVAP(I);
                           SS=SS-E/2; END;
          E=EVAP(I);     /* MOISTURE IN VS FROM PREVIOUS RAIN */
        IF VS>0
          THEN IF VS<E
                  THEN DO; US=US-(E-VS)/2;     /* EVAPN FROM */
                           SS=SS-(E-VS)/2;     /* US VS SS   */
                           VS=0; END;
                  ELSE DO; US=US;              /* EVAPN FROM */
                           SS=SS;               /* VS ONLY */
                           VS=VS-E; END;
                                /* INFILTRATION DS TO SS FROM PREVIOUS RAIN */
        IF DS>=F THEN DO; DS=DS-F;
                          SS=SS+F; END;
        IF DS<F THEN DO; DS=0;
                         SS=SS+DS; END;
           F=10+(426-10)*(2.71828**(-0.0058*SS));                /* CALC NEW F */
 ENDDAY: IF US<0 THEN US=0;
          IF SS<0 THEN SS=0;
          IF DS<0 THEN DS=0;
          P=0; Q=0;
        END;  END;  END;
        PUT SKIP (2); PUT LIST ('SIGQ=',SIGQ);
END YIELD;
```

Table 10.2: Descriptions of variables used in model calculations

Variable	Description
VSMAX	Interception store capacity.
VS	Volume of moisture in the interception store.
USMAX	Upper soil zone store capacity.
US	Volume of moisture in the upper soil zone store.
DSMAX	Drainage store capacity.
DS	Volume of moisture in the drainage store.
SSMAX	Lower soil zone store capacity (used in evaporation loss calculations only).
SS	Volume of moisture in the lower soil zone store.
P	Excess moisture after the initial loss stores (VSMAX, USMAX and DSMAX) have been filled by rainfall.
Q	Calculated volume of runoff.
F	Prevailing daily infiltration rate.
E	Daily evaporation rate selected and used in the calculations.
E(I)	Daily evaporation rate estimated from Commonwealth Bureau of Meteorology maps.

Table 10.3: Descriptions of the model functions shown in Fig. 41

Symbol	Model function
A	Replenish upper soil zone store and drainage store.
B	Calculate overflow from initial loss stores.
C	Calculate runoff.
D	Print date, runoff and values of variables.
E	Calculate evaporation from interception store, upper soil zone store and lower soil zone store.
F	Calculate infiltration from drainage store into lower soil zone store.
G	Calculate new infiltration rate for the next day.
H	Determine the prevailing evaporation rate for the upper soil zone.
I	Calculate evaporation loss from the upper soil zone store.
J	Determine the evaporation rate for the lower soil zone store.
K	Calculate evaporation loss from upper soil zone, lower soil zone and interception stores.

Catchment parameters (cont'd.)

SS	Volume of moisture in the lower soil store, pts.
Fo, K	The infiltration parameter Fo and its dependent K in the infiltration equation, $F = 10 + (Fc - 10)e^{-K.SS}$.

To commence the calculations the parameters VS and DS were set at zero, whilst US and SS were set at half the store capacities.

The zero values for VS and DS are reasonable, as the stores are both emptied soon after rainfall.

However if the assumed values of half capacity for US and SS were well removed from the correct values, then this would extend the length of the required warm-up period. To examine this aspect the model was operated on Badgerys Creek and Wagga Wagga catchment data with initial values for US of zero, half store capacity and store capacity, while SS and DS were set initially at half capacity. For US initially at zero and store capacity, the calculated runoff depths adjusted to within 1% of the depths estimated with US initially at half capacity after 2 - 6 months' operation of the model. A similar procedure for the parameter SS indicated an adjustment period of 16- 24 months. In both cases (testing of US and SS) the time for adjustment to within 5% was approximately half of that for adjustment to within 1%.

If possible, rainfall data for a period of at least 12 months, and preferably 24 months, before the runoff record commences should be used to achieve adjustment of the parameters.

10.2 Logic of programme

Although the basic structure of the model, as illustrated in Fig. 1 is very simple, the calculations for its operation are more complex. This is because of the many conditions which may arise and the necessity of preventing the variables assuming negative values.

As an example, the section of the model simulating infiltration into the lower soil zone store (SS) after rain, is illustrated in Fig. 42. The conditions which could occur and the calculations required to accommodate these conditions are shown in Table 10.4. The calculations are illustrated in diagram form in Fig. 43 and presented in PL1 language in Table 10.5. The other sections of the model were dealt with in a similar manner.

Table 10.4: Infiltration after rain. The conditions (variable values) which could occur in the model calculations and the resultant "drainage store" (DS) adjustments.

P - Q	DS	F	SS	Adjustments to DS	No. in Fig. 43
> 0	Then DS = DSMAX	Note: F > (P-Q) by defn. Then if, F < DS + (P-Q)	Then SS = SS + F	F = (P-Q) + remainder to make up F from DS store i.e. (F-(P-Q)) from DS ∴ DS = DS - (F-(P-Q))	(1)
		Then if, F > DS + (P-Q)	Then SS = SS+DS+(P-Q)	DS = 0	(2)
=0	Then if, DS = DSMAX	Then if, F > DSMAX	Then SS = SS + DSMAX (or DS)	DS = 0	(3)
		F = DSMAX	Then SS = SS + DSMAX (or DS or F)	DS = 0	(3)
		F < DSMAX (i.e. < DS)	Then SS = SS + F	DS = DS - F	(4)
	Then if, 0 < DS < DSMAX	Then if, F > DS	Then SS = SS + DS	DS = 0	(3)
		F = DS	SS = SS + DS (or F)	DS = 0	(3)
		F < DS	SS = SS + F	DS = DS - F	(4)
	Then if, DS = 0	Then if, F > 0 F = 0	Then SS = SS (+0)	DS = 0	(3)

Table 10.5: Infiltration calculations, for "RAIN:" section of model, in PL1 language

```
IF (P-Q) > 0                              /* INFILTRN DS TO SS*/
THEN IF F < DS + (P - Q)
   THEN DO;    SS = SS + F;
               DS = DS - (F - (P-Q) ); END;
   ELSE DO;    SS = SS + DS + (P- Q);
               DS = 0; END;

IF (P-Q) = 0
 THEN IF F > = DS
   THEN DO;      SS = SS + DS;
                 DS = 0; END;
   ELSE DO;      SS = SS + F;
                 DS = DS - F; END;

F = 10 + (426 - 10)* (2.71828* *(-0.0058*SS) );/* CALC NEW F*/
GO TO ENDDAY;
```

Table 10.6: Sample of computer printout from the Boughton model programme

Date	Rfall	Q	P	F	SS
16.1.55	147	22.19168	66.0	50.8	400.0
17.1.55	71	23.46046	59.9	40.4	450.8
29.1.55	96	14.03236	40.0	29.7	525.3
2.2.55	140	59.88311	84.0	24.1	582.7
3.2.55	6	0.00498	1.9	22.3	606.9
4.2.55	39	2.01501	14.6	20.8	629.2
12.3.55	120	47.40667	64.0	16.6	714.2
2.7.55	69	3.99279	13.0	10.7	1082.1
3.7.55	14	1.30418	8.2	10.7	1092.9
28.7.55	25	0.00464	1.1	10.3	1202.5
29.7.55	18	0.30742	4.7	10.3	1212.9
3.8.55	74	19.60635	29.8	10.2	1264.5
4.8.55	18	4.95243	13.9	10.2	1274.8
8.8.55	36	2.94474	11.0	10.2	1315.7
9.8.55	31	14.86373	24.9	10.1	1325.9
12.8.55	69	34.34310	44.4	10.1	1356.5
11.9.55	127	60.92477	71.0	10.0	1485.8
12.9.55	17	4.34554	12.9	10.0	1495.9
9.10.55	92	25.97924	36.0	10.0	1612.3
20.12.55	60	0.20016	4.0	10.0	1848.7
21.12.55	20	2.26121	9.7	10.0	1858.7

Table 10.7

Sample of computer printout from the Boughton model programme.

DATE	RFALL	Q	P	F	SS
16 1 55	147	22.19168	66.0	50.8	400.0
17 1 55	71	23.46046	59.9	40.4	450.8
29 1 55	96	14.03236	40.0	29.7	525.3
2 2 55	140	59.88311	84.0	24.1	582.7
3 2 55	6	0.00498	1.9	22.3	606.9
4 2 55	39	2.01501	14.6	20.8	629.2
12 3 55	120	47.40667	64.0	16.6	714.2
2 7 55	69	3.99279	13.0	10.7	1082.1
3 7 55	14	1.30418	8.2	10.7	1092.9
28 7 55	25	0.00464	1.1	10.3	1202.5
29 7 55	18	0.30742	4.7	10.3	1212.9
3 8 55	74	19.60635	29.8	10.2	1264.5
4 8 55	18	4.95243	13.9	10.2	1274.8
8 8 55	36	2.94474	11.0	10.2	1315.7
9 8 55	31	14.86373	24.9	10.1	1325.9
12 8 55	69	34.34310	44.4	10.1	1356.5
11 9 55	127	60.92477	71.0	10.0	1485.8
12 9 55	17	4.34554	12.9	10.0	1495.9
9 10 55	92	25.97924	36.0	10.0	1612.3
20 12 55	60	0.20016	4.0	10.0	1848.7
21 12 55	20	2.26121	9.7	10.0	1858.7

10.3 Subsoil depletion factor

The daily subsoil depletion factor of 0.999 used by Boughton was considered minor compared with the other parameters and was omitted from the model. The benefit gained by eliminating a minor parameter was regarded as offsetting a small loss, if any, in accuracy.

The function of the depletion factor is to reduce the value of the lower soil store by 0.1% per day. No limit was set on the capacity of the lower soil store and the average maximum value reached for the three N.S.W. catchments was near 1000 pts. Thus the depletion factor would have a maximum effect of reducing the lower soil store (SS) by 1 pt/day, which is not very significant for a parameter which varies without an upper limit.

By eliminating this parameter the results became more sensitive to the remaining more important parameters, which could then be more readily optimised.

10.4 Printout

For each day of calculated runoff, the computer prints the date, runoff and value of the parameters P, F and SS. The three parameter values may be used to estimate an infiltration curve which will produce better results on the next computer run.

An example of the printout is shown in Table 10.6.

11. TESTING OF DESIGN METHOD

The procedures developed for estimating the model parameters were tested by application to an independent catchment. The estimated and recorded runoff values over a period of 11 years were then compared.

The catchment chosen was that of Parwan Weir, operated by the Soil Conservation Authority of Victoria. The rainfall and runoff data were supplied by the Authority.

11.1 Parwan Weir catchment

The 210 acre Parwan Weir catchment is located 10 ml. W.S.W. of Bacchus Marsh, Victoria and had recorded annual rainfalls during the 1956-66 test period as listed in Table 11.1, with a mean of 20.75 in. An average annual evaporation of 42.5 in was estimated from a Commonwealth Bureau of Meteorology evaporation map, and, with the above mean rainfall, the climate index (C) was 0.487.

The vegetation comprises low grade natural pasture with a small proportion of perennial grasses and a few trees, providing approximately 55% ground cover. Considerable sheet erosion exists on the steep portion of the catchment, with gulley and tunnel erosion in the water courses.

A slightly gravelly fine clay loam topsoil is located above red clay, which merges with white clay at a lower level.

The average slope of the catchment was estimated to be 11% by the grid contour intersection method.

This catchment is similar to Wagga Wagga in that the latter had mean annual rainfall and evaporation values of 22 in and 45 in and a climate index of 0.488, during the period 1951-59 for which data were available, and both catchments were subject to many dry periods. The slope of Wagga Wagga catchment was estimated as 12.4%.

Table 11.1: Annual rainfall data for Parwan Weir catchment

Year	Annual rainfall, ins
1956	23.06
1957	15.46
1958	17.26
1959	19.70
1960	24.60

Table 11.1 (cont'd.) Annual rainfall data for Parwan Weir catchment

Year	Annual rainfall, ins
1961	15.61
1962	17.44
1963	26.07
1964	28.10
1965	17.54
1966	23.51
Mean	20.75

11.2 Estimation of parameters

The parameters which it was necessary to estimate were:-

Interception store capacity	VSMAX
Drainage store capacity	DSMAX
Upper soil store capacity	USMAX
Lower soil store capacity	SSMAX
Infiltration parameters	Fo and its dependent K
Monthly evaporation values	E(I)

The parameters were estimated as follows:-

Interception store capacity

For the vegetal cover of 55% on Parwan Weir catchment, Table 9.6 specifies a value of 3 pts for VSMAX.

Drainage store capacity

For a climate index of 0.487, DSMAX was estimated from Fig. 25 to be 46 pts. An inspection of Parwan Weir catchment was not made and this value of DSMAX was not compared with a field estimate based on upper soil zone depth and NCP.

Upper soil store capacity

The upper soil zone depth on Wagga Wagga catchment was measured as 2" and this depth was adopted for Parwan Weir, on the basis of climatic and descriptive similarity between the two catchments. For a 2" depth and available water capacity (AWC) of 2"/ft (Fig. 11, fine clay loam) the store capacity is 33 pts.

Lower soil store capacity

In the calculations there is no upper limit on the amount of moisture in the lower soil store. As discussed in Section 6.4, SSMAX is a pseudo-parameter and is used for calculating the evaporation loss from the lower soil store.

A value of 1000 pts was used for SSMAX in the test run, this having been indicated as satisfactory during the model runs on the N.S.W. catchments. (Section 6.4).

Infiltration parameters

For a catchment slope of 11%, Fo was estimated as 430 pts from Fig. 38 and K as 0.0058 from Fig. 36.

Monthly evaporation

Average monthly evaporation values were estimated from maps published by the Commonwealth Bureau of Meteorology. Penman factors of 0.8 (summer), 0.7 (spring and autumn) and 0.5 (winter) were applied to provide estimates of evapotranspiration. The mean daily value for each month of the year was then calculated for input to the model.

Initial parameter values

As discussed in Section 10.1, the calculations were commenced with initial values of VS and DS equal to zero, while SS and US were set at half store capacity. A period of 12 months was used to warm up the calculations.

11.3 Test run results

The recorded and estimated runoff depths are listed in Table 11.2. The results from Parwan Weir were compared with those from the three N.S.W. catchments used in the derivation of the design procedure. The estimated and recorded mass curves for Parwan Weir are shown in Fig. 44 and for the three N.S.W. catchments in Figs. 45-47. The initial run on Parwan Weir produced a mass curve which was not far removed from the recorded curve during the period 1956-62, but diverged over the next four years, from 1963-66. Visual comparison indicates the divergence for 1963 and most of 1964 to be of the same order as that obtained for similar length periods for the N.S.W. catchments.

Results from a relative frequency of runoff analysis are compared in Table 11.3. For this analysis, an occasion when either the recorded or estimated runoff was equal to or greater than 0.07 pts was defined as a runoff event. The frequency diagrams are presented in Figs. 48-51.

For each catchment the Kolmogorov-Smirnov test (Lindgren, 1962) was used to test the agreement between the cumulative frequency curves of recorded and estimated runoff. This is an appropriate statistical test for comparing empirical distributions. For each of the three N.S.W. catchments, the test indicated very good agreement between the recorded and estimated curves over their entire range. For Parwan the agreement between the two curves was very good except in the region near zero runoff. This inconsistency emphasises the failure of the model to predict low runoff events. However, the adverse result near zero runoff for Parwan is not considered very important as regards the test of the design method, for the following reasons:-

(i) For the eleven year test period, the sum of all recorded runoff events less than two points was only 6.5% of the total runoff.

(ii) The result indicated by the Kolmogorov-Smirnov test is largely dependent upon the definition of a runoff event (i.e. the sample size). For example, if a possible runoff event was defined as each day of record or each occasion of rainfall (instead of 0.07 pts or more of runoff), then the Kolmogorov-Smirnov test would indicate very good agreement between the frequency curves over their entire range for Parwan catchment.

A frequency distribution test is not very appropriate to this work, because the temporal comparison of runoff is ignored and a good statistical result could be indicated for mass curves which diverge widely with respect to time. Direct comparison of the recorded and estimated mass curves is considered the most realistic basis for judging the test results. Visual inspection shows the results for Parwan to be good for the first seven years and fair for the last four years.

11.4 Optimisation of parameters

The results for the test run were acceptable. However, it was considered that more information on the performance of the design method could be obtained if the parameters were adjusted or optimised to produce a better result.

Table 11.2: Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q estimated, pts	
			Test run DSMAX=46	Optimum DSMAX = 35
2-3.5.56	63	3.25	0	0
12-13.5.56	98	13.90	0.19	0.40
	48			
16-17.5.56	33 30	2.69	0	0
5.6.56	20	0.01	0	0
17.6.56	31	0.12	0	0
1.7.56	18	0.53	0	0
7.7.56	44	3.94	0	0
17.7.56	32	2.49	0	0
30.7.56	30	0.27	0	0
8.8.56	32	0.86	0	0
10-11.8.56	22 23	0.74	0	0
14-15.8.56	18 35	8.13	0	0
25.8.56	22	0.89	0	0
28.8.56	17	1.35	0	0
2.9.56	47	3.52	0	0.03
9-11.9.56	101 107 26	55.60	105.1	114 .22
12.9.56	19	0.11	0.90	0.78
6-7.10.56	57.5 18.5	1.09	0	0.12
17.10.56	42	0.77	0	0
19.10.56	63	3.53	1.50	7.37
16.11.56	46	0.03	0	0
21-22.6.57	83 57	1.78	0	0.04
10-12.7.57	64 147 60	20.22	8.59	11.62
23.7.57	36	0.69	0	0
11.8.57	29.5	2.57	0	0
2.10.57	17	2.64	0	0.14
23.10.57	94	3.82	0.83	2.26
26.12.57	85	1.17	0	0.02
20-21.2.58	72 20	0.24	0	0.04

Table 11.2 (cont'd.) Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q estimated, pts	
			Test run DSMAX=46	Optimum DSMAX=35
14.4.58	41	0.34	0	0
13.5.58	77	1.16	0	0.01
15-16.5.58	8 13	0.04	0	0
19.5.58	37.5	0.50	0	0
24-25.5.58	15 8	0.53	0	0
26.5.58	27	0.55	0	0
29.7.58	45	0.92	0	0
15.8.58	92	5.64	0.73	1.56
25.8.58	32	0.04	0	0
12.9.58	31	0.09	0	0
17.9.58	32	0.32	0	0
3.10.58	11	0.14	0	0
5.10.58	21	0.44	0	0
11.10.58	34	0.08	0	0
16.10.58	34.5	0.52	0	0
21.10.58	26	0.10	0	0
13.11.58	63	1.05	0	0
10.12.58	46	0.20	0	0
9.2.59	88	2.10	0	0.01
14.2.59	114	6.00	0.21	0.46
4.3.59	165	10.92	3.40	4.84
5.3.59	20.5	0.16	0	0
10.3.59	47	0.59	0	0
27.3.59	43	0.02	0	0
31.3.59	73	0.48	0	0.06
30.6.59	31	0.01	0	0
6.8.59	26.5	0.40	0	0
13.8.59	25	0.60	0	0
1.9.59	35	0.20	0	0
19-21.9.59	130	2.50	7.88	11.49
20-21.10.59	43 82	2.60	1.00	2.32
27.11.59	160	10.34	6.90	9.61
18.12.59	42	0.06	0	0
25.12.59	123	1.35	0.80	1.53
28.12.59	12.5	0.01	0	0
31.1.60	65	0.93	0	0

Table 11.2 (cont'd.) Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q estimated, pts	
			Test run DSMAX=46	Optimum DSMAX=35
21-26.4.60	242) 70) 93) 49)	45.57	12.86	17.61
1-2.5.60	8) 58)	4.00	0	0.14
4-8.5.60	55) 62) 14) 21) 8)	8.10	1.28	4.39
12-13.5.60	37 2	2.62	0	0
12.6.60	15.5	0.42	0	0
5-6.7.60	16	0.68	0	0
13-14.7.60	24) 12.5)	1.49	0	0
19-20.7.60	27.5 38	8.30	0	0.01
23.7.60	18	0.66	0	0
13-14.8.60	18.5 31.5	2.72	0	0
19.8.60	29	0.37	0	0
20.8.60	40	3.30	0	1.54
29.8.60	37.5	0.55	0	0
7-8.9.60	2 65.5	5.10	0.04	2.98
14-15.9.60	45 21	3.50	0	0
17-21.9.60	62 13.5	9.10	3.50	9.98
24-26.9.60	19 132 19	6.30	73.90	84.11
13.11.60	101	3.90	32.80	42.50
3.12.60	32	0.75	0	0
1.1.61	117	0	11.70	16.10
1-2.3.61	85	0.03	0	0.04

Table 11.2 (cont'd.) Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q, estimated, pts	
			Test run DSMAX=46	Optimum DSMAX=35
17.6.61	50	0.15	0	0.01
6.7.61	25	0.07	0	0
7.7.61	37	0.14	0	0
23-24.7.61	36 53	3.80	0.003	0.15
17-18.8.61	46	0.07	0	0.01
21.8.61	22	0.20	0	0
23-24.8.61	14 38	2.50	0	0
30.8.61	22	0.05	0	0
14-15.12.61	71.5	0.19	0	0
28.3.62	60	0.40	0	0
17.5.62	61	0.38	0	0.01
29-30.5.62	34 25	0.07	0	0
2.6.62	25	0.01	0	0
6.6.62	19	0.03	0	0
9.6.62	28	0.13	0	0
24-25.7.62	124 5	20.00	6.30	9.40
1-2.8.62	21 24	1.35	0	0
21-22.8.62	47 17	1.87	0	0.03
30.8.62	25	0.18	0	0
24-25.9.62	48 51	7.20	6.25	0.19
5.10.62	34	0.66	0	0
6.10.62	19	0.11	0	0
10.10.62	24	0.06	0	0
23.10.62	31	0.16	0	0
24.10.62	17	0.30	0	0
4.12.62	38	0.02	0	0
28-30.1.63	124 329 9	69.00	92.83	100.32
10-11.2.63	27 131	80.50	10.90	15.06

Table 11.2 (cont'd.) Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q, estimated, pts	
			Test run DSMAX=46	Optimum DSMAX=35
24.3.63	67	0.90	0	0
30.4.63 to 1.5.63	150 68	10.40	2.08	3.47
14-17.5.63	31 70 68 79	41.00	5.60	11.67
26-27.5.63	36 45	9.80	0	0.10
2-3.6.63	35 13	3.90	0	0
13-14.7.63	130	21.50	57.31	67.76
29.7.63	26	0.40	0	0
5.8.63	38	1.10	0	0
11-12.9.63	34 24	0.84	0	0
15.9.63	21	0.63	0	0
23-24.9.63	15 27	0.23	0	0
29-30.9.63	50 92	25	41.90	50.79
1.10.63	12	0	0.52	0.47
12.10.63	58	0.51	0	0
21.10.63	54	1.07	0	0
6-7.12.63	101 9	1.15	2.10	5.55
10-11.2.64	104 123	21.80	9.57	12.72
1.3.64	54	0.64	0	0
7-9.4.64	5 158 158	45.00	31.23	37.17
20-21.4.64	40 118	21.80	17.00	21.97
2-4.6.64	10 41	1.50	0	0
3-4.7.64	55 21	6.20	0	0.05

Table 11.2 (cont'd.) Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q estimated, pts	
			Test run DSMAX=46	Optimum DSMAX=35
12-13.7.64	22 32	3.80	0	0
14-15.7.64	6 17	1.10	0	0
16-17.7.64	18 73	23.80	3.83	9.27
20.7.64	17	0.30	0	0
24-25.7.64	31 2	2.20	0	0
5-6.8.64	30 1	1.80	0	0
9-10.8.64	34 5	1.95	0	0
11-12.8.64	27 5	4.08	0	0
4.9.64	38	3.96	0	0
8.9.64	18	0.21	0	0
11-12.9.64	84 51	35.40	42.80	51.30
16.9.64	32	0.80	0	0
29-30.9.64	64 3	3.95	0.06	3.03
2.10.64	41	4.20	0	0
4.10.64	19	0.24	0	0
6-7.10.64	22 6	0.76	0	0
8.10.64	74	20.60	10.68	20.37
10.10.64	19	0.04	0	0
17.10.64	30	0.80	0	0
18-19.11.64	129	10.50	32.60	41.81
	90	21.20	68.15	66.57
9.12.64	93	2.87	1.42	6.25
10.12.64	20	0.03	0.07	0.28
20.4.65	96	1.67	0.49	0.83
22.4.65	24	0.29	0	0
23.4.65	48	2.75	0	0.01
22.6.65	60	1.86	0	0.02
23.6.65	14	0.03	0	0
11.7.65	39	0.33	0	0

Table 11.2 (cont'd.) Parwan Weir catchment, recorded and estimated runoff depths (Q, pts)

Date	Rainfall, pts	Q recorded, pts	Q estimated, pts Test run DSMAX=46	Optimum DSMAX=35
13.7.65	25	0.15	0	0
27.7.65	9	0.34	0	0
* 7.8.65	212	0	113.93	121.23
13.8.65	16	0.05	0	0
16.8.65	52	0	0.007	0.52
6.9.65	20	0.38	0	0
25.11.65	84	0.21	1.06	1.70
1.12.65	60	0.32	0	0
6.12.65	19	0.03	0	0
13.2.66	266	28.22	23.37	23.84
14.2.66	14	0.05	0	0
16.3.66	74	2.13	0	0
19.3.66	27	1.10	0	0
20.3.66	32	0.11	0	0
22.4.66	110	3.90	0.24	0.56
30.4.66	22	0.20	0	0
5.5.66	41	0.71	0	0
6.7.66	26	0.03	0	0
15.7.66	19	0.08	0	0
26.7.66	7	0.12	0	0
27.7.66	24	0.14	0	0
10.8 66	88	5.57	0.28	0.73
12.8.66	36	1.38	0	0
19.8.66	38	1.25	0	0
20.8.66	11	.12	0	0
22.8.66	25	1.11	0	0
23.8.66	11	0.25	0	0
24.8.66	9	0.07	0	0
16.9.66	29	0.17	0	0
17.9 66	27	0.88	0	0
4.10.66	21	0.02	0	0
5.10.66	37	1.50	0	0
20.10.66	125	36.51	3.98	6.95
13.11.66	39	3.14	0	0
3.12.66	44	0.16	0	0
4.12.66	56	0	0	0.05
5.12.66	212	68.31	80.86	90.10
26.12.66	56	1.91	0	0.01
	Totals	1015.5	827.3	1009.4

* Runoff event of 7.8.65 discarded as recording error.

Table 11.3: Frequency of runoff analysis

Catchment		Runoff class range, pts depth				
		.07-4	4-16	16-64	64-256	>256
Badgerys Creek	R	26.1	21.7	26.1	26.1	0
	E	30.4	21.8	26.1	17.4	4.3
Scone	R	55.6	25.0	16.6	2.8	0
	E	72.2	11.1	13.9	2.8	0
Wagga Wagga	R	64.4	25.0	9.6	1.0	0
	E	75.9	12.5	9.6	2.9	0
Parwan	R	78.3	11.1	8.9	1.7	0
Test run: DSMAX = 46	E	86.7	6.1	4.4	2.8	0
Optimum run: DSMAX = 35	E	82.8	8.3	5.6	3.3	0

R: recorded runoff
E: estimated runoff

From previous experience it was known that the results could be improved by optimising either DSMAX or the interdependent infiltration parameter (Fo). The former provided the simpler method and was consequently adopted.

Optimisation of DSMAX showed that a value of 35 pts produced the best result on a (Σ Q rec. - Σ Q calc.) basis. (The use of this criterion for comparing the estimated and recorded runoff was discussed in Section 5.2.1). The mass curve for this value of DSMAX is shown in Fig. 44 and the agreement between this and the recorded curve is comparable to the best mass curve result for the N.S.W. catchments (Wagga Wagga).

A frequency analysis of the optimum results is listed in Table 11.3 and illustrated in Fig. 51. Again, the Kolmogorov-Smirnov test indicated very good agreement between the recorded and estimated frequency curves except near zero runoff. Notwithstanding this, the result for the optimum DSMAX is considered to be good.

11.5 Discussion of results

The result obtained for the test run on Parwan Weir data is comparable to the average result for the three catchments used in the derivation of the design method.

In the Boughton model, the two parameters, infiltration (Fo) and drainage store capacity (DSMAX), are inter-dependent and may be optimised to produce good results. In this study these two parameters were correlated with physical catchment properties, "Fo Vs catchment slope ($\mathcal{S}$)" and "DSMAX Vs climate index (C)". The former correlation was established on 5 points of data and the latter on 3 points. Although the results from the test run on Parwan Weir data indicate that the two correlations are reasonable, the correlations should be examined by analysis of the data from more catchments.

The Parwan Weir results provided a brief opportunity to investigate the correlations and this will be described.

To examine the "Fo Vs $\mathcal{S}$" correlation, the infiltration curve shown in Fig. 52 was estimated, from the test run computer printout for Parwan Weir, by the method described in Section 7.4. The curve has the parameter (Fo = 300 pts) and the point (Fo = 300 pts, $\mathcal{S}$ = 11%) is compared with the derived "Fo Vs $\mathcal{S}$" correlation in Fig. 53. This point is within the 99.7% confidence limits of the correlation curve and indicates support for the correlation.

To examine the "DSMAX Vs C" correlation, the derived optimum value of DSMAX (35 pts) for Parwan Weir is compared with the "DSMAX Vs C" correlation in Fig. 54. This point (DSMAX = 35, C = 0.487) is not located within the 99.7% confidence limits of the correlation curve. The infiltration curve parameter used with the optimum value of DSMAX is located on the correlation curve for "Fo Vs $\mathcal{S}$" in Fig. 38 (i.e. the point Fo = 430 pts, $\mathcal{S}$ = 11%). As only 3 points were used in the derivation of the DSMAX correlation, it is not considered that any conclusions can be drawn from the divergence of the point (35, 0.487). Also, an error in DSMAX could be partly attributable to looseness in the infiltration parameters, the correlation for which is only based on 5 points.

A further matter is raised by the variability of the annual rainfall on Parwan Weir catchment (Table 11.1). During the 11 year test period the annual rainfall varied from 15.5 in to 28.1 in, with a 3 year drought over the period 1957-59, when the annual rainfall did not exceed 19.7 in. Under these conditions, the catchment vegetation and consequently the soil structure, would be subject to wide variations. It was shown in Section 5.3.1 that very significant variations may occur in upper soil NCP during a given year. The variation would be greater over an eleven year period which had marked differences in annual rainfall. It is therefore apparent that even optimum values of the parameters would only represent the average condition of the catchment.

Because of this temporal variation in the physical properties of catchment topsoil, the one set of parameters would not be expected to produce accurate estimates of runoff, for all runoff events, over a period of years with variable annual rainfall.

It may be accepted that the model will under-estimate some runoff events and over-estimate others, depending on the physical condition of the catchment at the time, compared with its average condition as represented by the model parameter values.

This behaviour of the model, was apparent in the results for Parwan Weir and the N.S.W. catchments, with optimum parameter values balancing the effect. Very small runoff events were the most difficult to estimate.

To obtain more accurate estimation of individual runoff events it would be necessary to vary the initial loss parameter values with time. This would complicate the model considerably and could hardly be justified for yield studies at present.

12. CONCLUSIONS

The first part of this chapter (Section 12.1) states the original objectives and then examines the achievements of the project.

The second part (Section 12.2) contains a number of suggestions for future research and states the main obstacle to progress.

12.1 Achievement of objectives

The two main objectives of the study were:-

(i) to reduce the number of parameters in the Boughton model, and

(ii) to establish objective methods for estimating the true "in nature" values of the remaining parameters, which would also produce good results for the model's operation.

The reduction of the parameters (Section 12.1.1) and the success and limitation of the design method, in its application (Section 12.1.2) are first described.

Next, the success in relating the model parameters to true physical values is discussed (Section 12.1.3).

12.1.1 Reduction of parameters

In Section 2.1 it was specified as necessary to evaluate the following parameters for application of the model to a catchment:-

(i) Moisture store capacities

Interception store	VSMAX
Upper soil store	USMAX
Drainage store	DSMAX
Lower soil store	SSMAX

(ii) Evaporation parameters

Percentage of evaporation occurring from the upper soil store (remainder occurs from the lower soil store).

Maximum evaporation rate.

(iii) Infiltration parameters

The parameters Fo, Fc and K in the equation,
$F = Fc + (Fo - Fc)\ e^{-KS}$.

(iv) Transmission loss

Increase in initial loss with increasing catchment area.

(v) Groundwater

The subsoil depletion factor.

In the recommended design method, parameters have been eliminated or set constant as follows:-

(i) Moisture store capacities

No limit placed on the capacity of the lower soil store. For evaporation calculations, a constant value of 1000 pts was adopted for SSMAX.

(ii) Evaporation parameters

A proportion of 50% was adopted for evaporation from the upper soil store. The maximum evaporation rate was set constant at 35 pts/day. (Both of these actions are as employed by Boughton, 1965).

(iii) Infiltration parameters

The parameter Fc was set constant at 10 pts/day and K was made a dependant of Fo, thus eliminating two parameters.

(iv) Transmission loss

The problem of transmission loss was avoided by limiting the project to small catchments.

(v) Groundwater

A study of the literature indicated that groundwater was not important for small catchments and the subsoil depletion factor was deleted from the model.

The nett result was for six parameters (SSMAX, Fc, K, two evaporation, subsoil depletion factor) to be eliminated or set constant, leaving four parameters (VSMAX, USMAX, DSMAX, Fo) to be objectively estimated for application of the model to a catchment.

12.1.2 Success and limitations of the design method

The results for the test run on Parwan Weir data approached the average results for the catchments used in the derivation of the design method. The test of the method is therefore considered to have been successful.

The design procedure should produce satisfactory results for catchments of similar physical characteristics and geographic location to the catchments used in the derivation. This implies the following conditions:-

Location: In a general area of eastern N.S.W. and Victoria including Scone, Badgerys Creek, Wagga Wagga and Parwan Weir catchments, with a climate index (as defined in Section 5.2.2) in the range of 0.4 - 0.8.

Slope: Within the range 4 - 20%.

Area: The areas of the catchments used for deriving and testing the procedure were:-

Badgerys Creek	(15 acres)
Wagga Wagga	(20 acres)
Scone	(40 acres)
Parwan Weir	(210 acres)

Land use: Natural grassed catchments.

12.1.3 Physical significance and validity of parameter design values

The four model parameters (VSMAX, USMAX, DSMAX, Fo), which it is necessary to estimate, will be examined with respect to their physical significance and their validity in relation to the true values of the catchment components which they represent.

Interception store capacities

The parameter VSMAX is directly related to a single physical catchment component and the derived design values are supported by analysis of many physical measurements.

Soil store capacities

The two soil moisture storage parameters USMAX and DSMAX each represent the product of the upper soil depth and a soil moisture constant (AWC for USMAX and NCP for DSMAX). Topsoil depth is a measurable quantity, while the analysis of considerable data has provided design values for estimating AWC from soil texture (Section 5.1.3.2).

Alternatively, topsoil depth may be estimated by comparing the climate, location and land use of a catchment with the catchments used for deriving the design method.

The estimation of DSMAX was later removed from a separate component basis and the model parameter related directly to climate, a factor which controls the separate physical components.

Values of USMAX and DSMAX estimated by the methods recommended in this report should be near to the true values.

Infiltration parameter

The infiltration parameter, Fo, was correlated with catchment slope and was stated to represent infiltration from the upper soil into the transition soil, with a consequent flow of water downhill through the transition soil.

Information has been presented which permits estimation of infiltration rates through soils of various textures and over a range of initial moisture contents. This information may be used to check on the limiting infiltration rates for any part of a soil profile.

The slope of a catchment is readily estimated and its relative effect on the infiltration parameter may then be appraised.

Infiltration is a complex process and it would be difficult to establish beyond doubt that the model's simulation of infiltration, as stated in this report, is completely valid. Nevertheless, the infiltration curves were derived with all other parameters as close as possible to the true values, and the curves also accord with known infiltration rates and behaviour.

It is considered that the design method for the infiltration parameter is realistic.

In conclusion, the discussion in this section has related the four variable model parameters directly to catchment components and indicated the derivation, or method of checking, the design values from simple measurable physical properties.

12.2 Future research

Four suggestions are made in this section. The first two (Section 12.2.1) refer to improvement of the design procedure which has been developed, while the third (Section 12.2.2) indicates a direction of research for future development in the field of yield estimation. Finally, the main obstacle to be overcome is stated (Section 12.2.3).

12.2.1 Improvement of design procedure

To apply the model to an ungauged catchment it is necessary to estimate four parameters, which may be listed under two model operations as follows:-

Initial loss	VSMAX
	USMAX
	DSMAX
Infiltration	Fo

Consideration of these parameters suggests two avenues for improving the design method.

Firstly, it should be possible to further reduce the number of parameters. Three parameters appears excessive for the initial loss section, particularly as the value of VSMAX is generally in the order of 4-5% of the combined values of USMAX and DSMAX. All three initial loss parameters are dependent upon vegetation, which is related to climate. It should be possible to reduce the number of initial loss parameters at least by one, to two, which could then be correlated with climate, for natural grassed catchments. Catchment treatment could also be later employed in the correlation.

Secondly, the correlations of "Fo Vs ρ " and "DSMAX Vs C" which have been derived, are based on a few points and need to be examined with the data from many more catchments.

12.2.2 Further development of design procedure

With further research it should be possible to apply the model with confidence to ungauged catchments throughout N.S.W. Long term rainfall data (80 years) for climatic regions could be processed by the model over ranges of parameter values to produce long term runoff data. The runoff data could then be analysed and "storage capacity Vs reliability" design data presented on a regional basis, for various types of land use.

The storm types and catchment conditions which caused major floods could also then be determined and employed in flood estimation research.

12.2.3 Present deficiency

The main obstacle to progress with the model is the lack of suitable data. Although a fair number of small gauged catchments have been listed (Australian Water Resources Council, 1967), closer examination indicates that, in N.S.W. at least, many of the catchments are not suitable for the required purpose or do not yet have adequate records.

The author supports the finding of the Australian Water Resources Council (1968) that the presentation of reliable rainfall - runoff data in computer compatible form is the prime requirement for research in yield studies at present.

ACKNOWLEDGEMENTS

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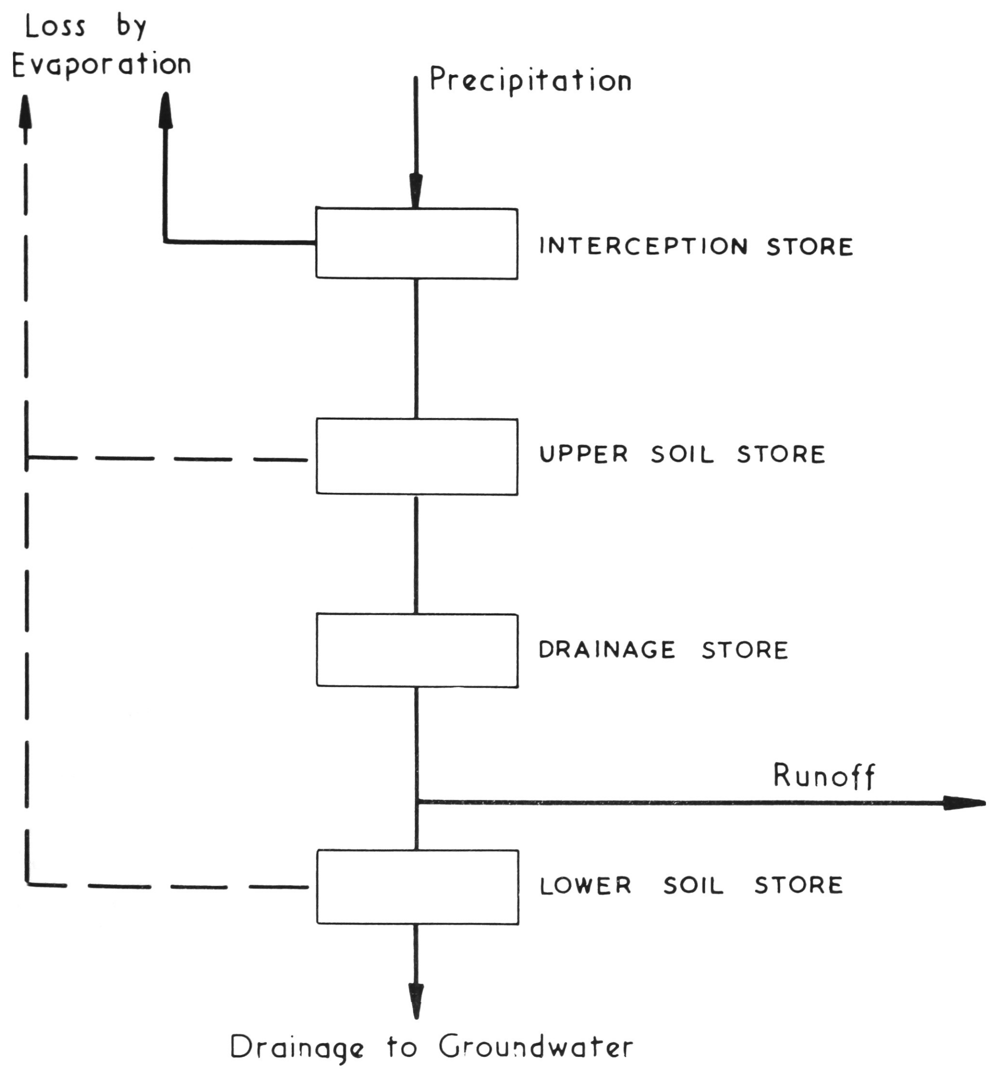


FIGURE 1: BOUGHTON'S MODEL

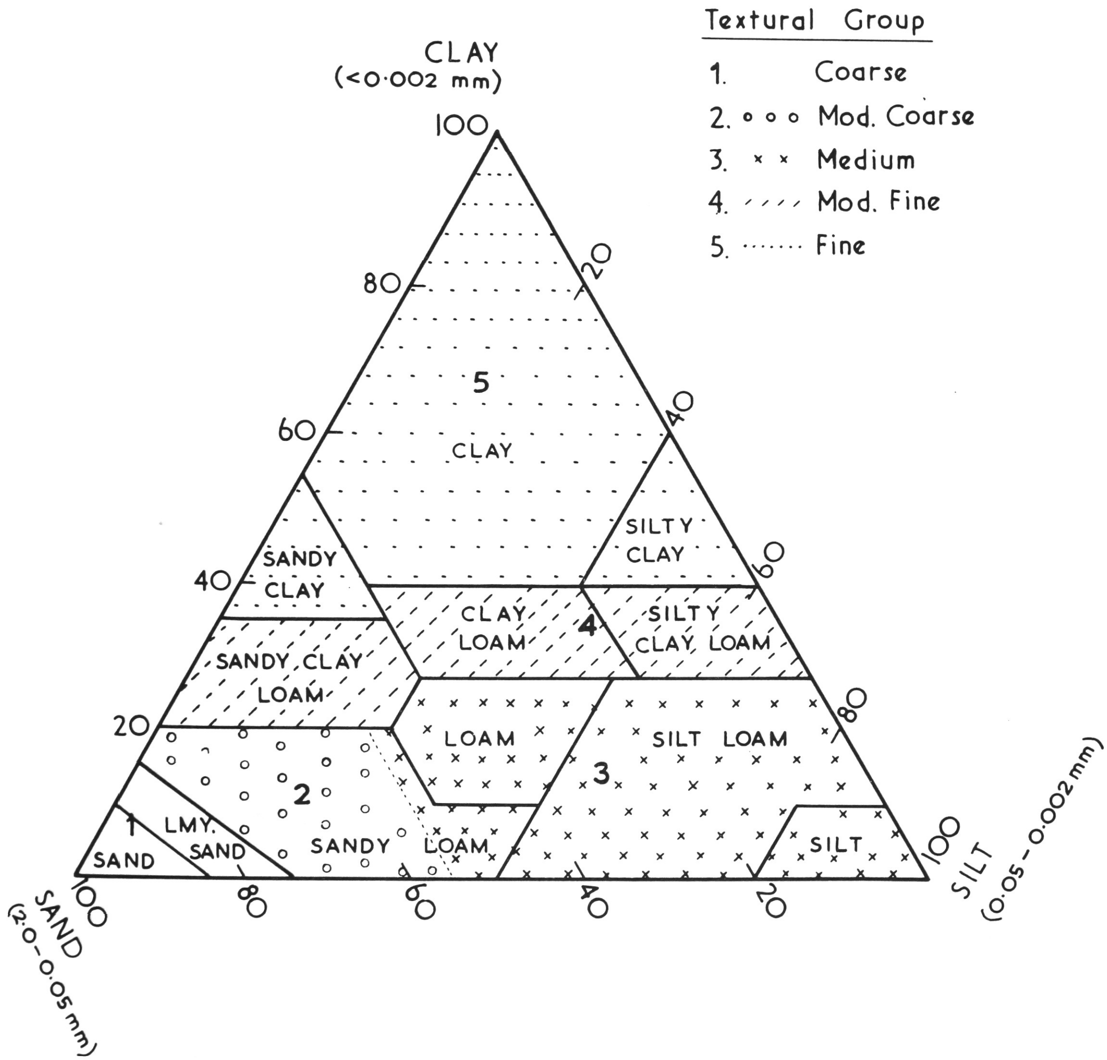


FIGURE 2: USDA TEXTURAL CLASS TRIANGLE SHOWING USDA TEXTURAL GROUPS.

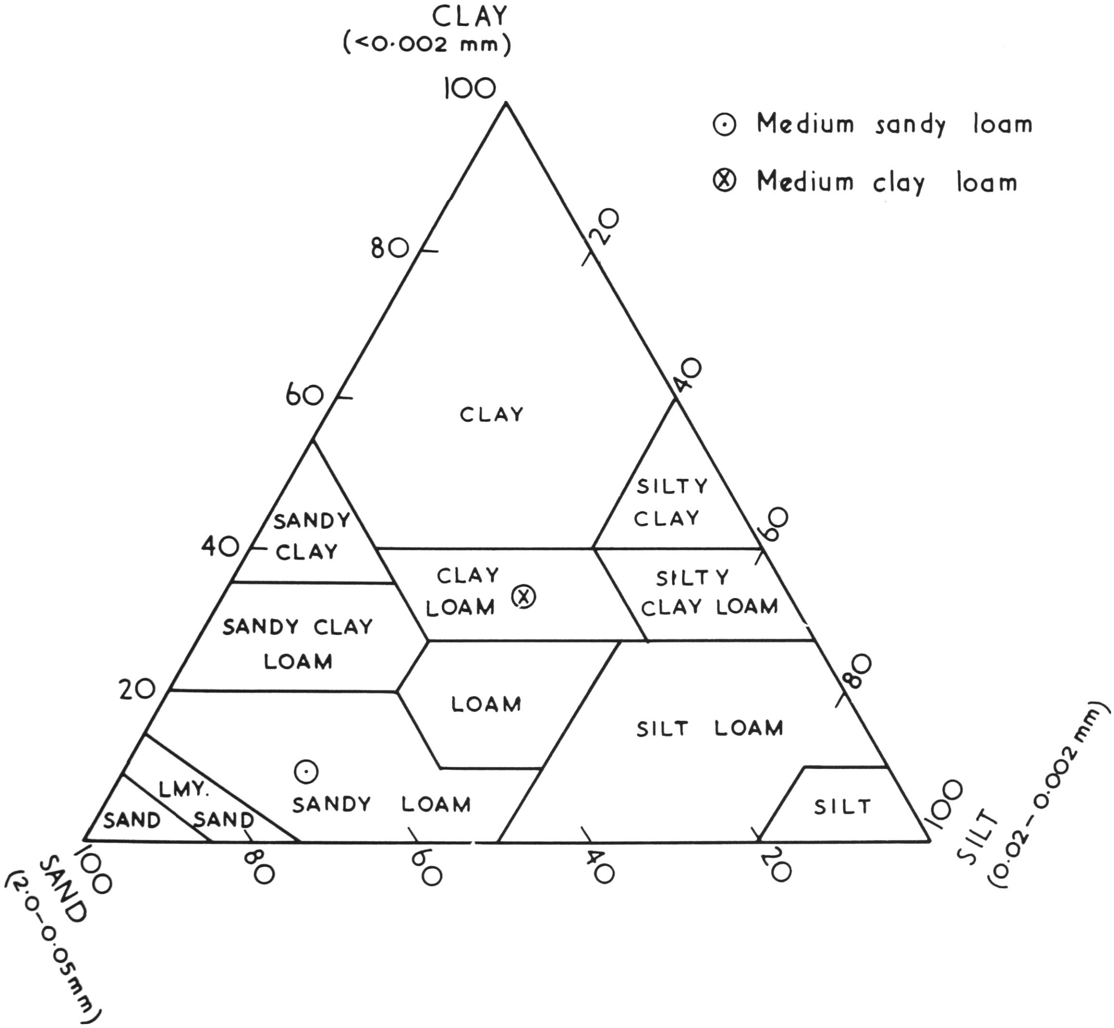


FIGURE 3: USDA TEXTURAL CLASS TRIANGLE SHOWING CLASSIFICATION OF 2 TYPICAL SOILS

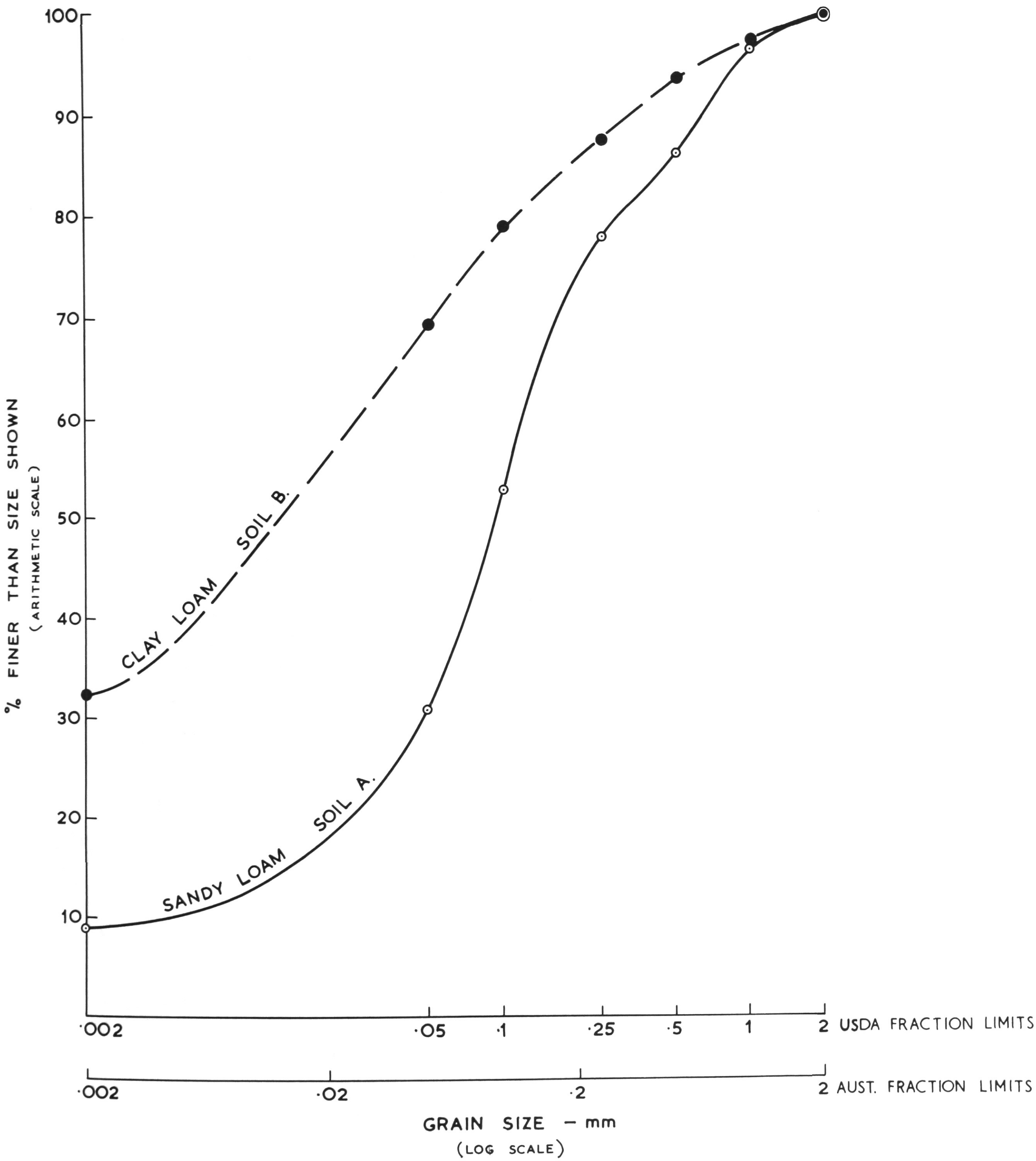


FIGURE 4: TRANSPOSITION FROM USDA TO AUST. SOIL TEXTURAL CLASSIFICATION SYSTEM

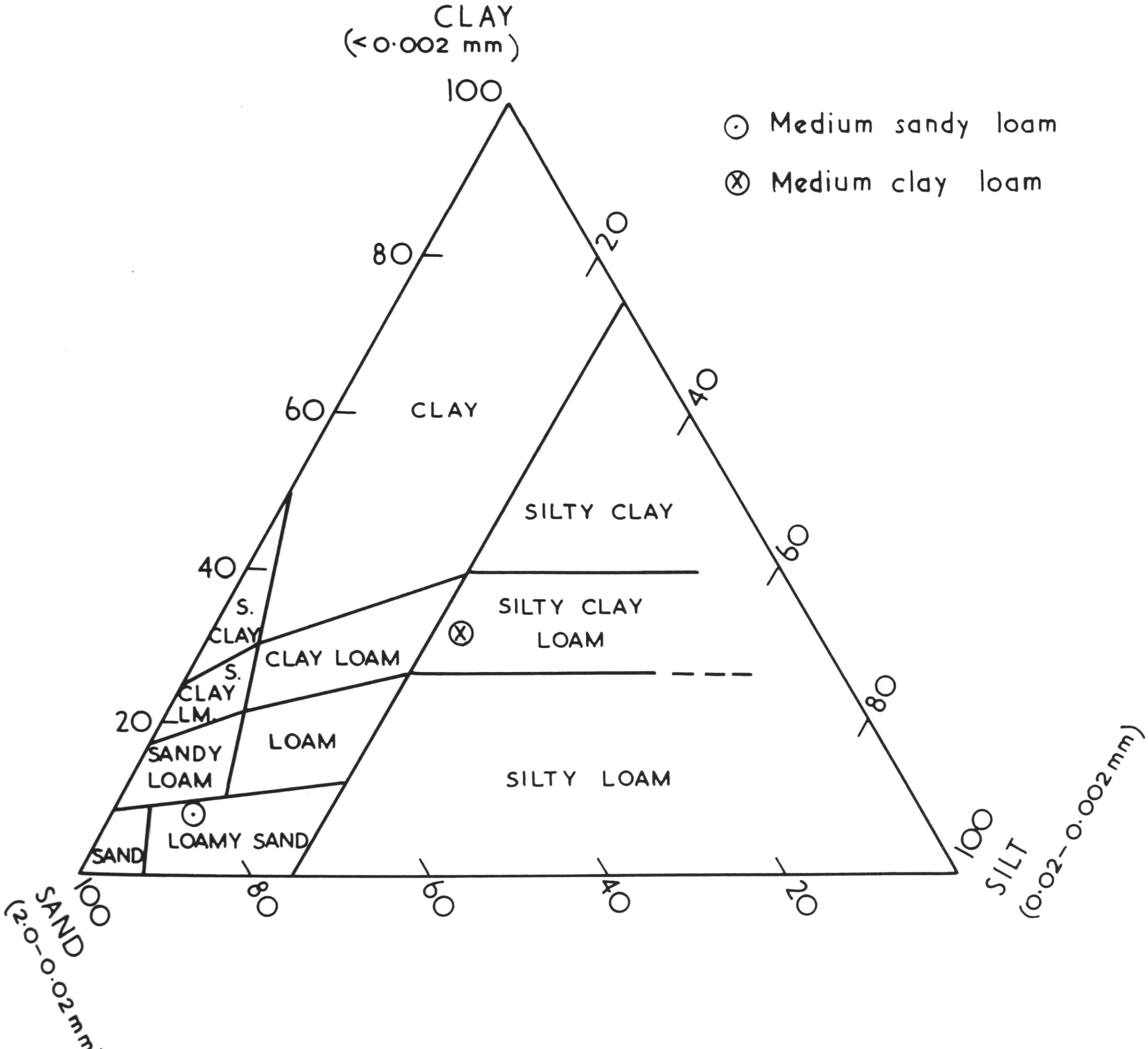


FIGURE 5: AUSTRALIAN TEXTURAL CLASS TRIANGLE SHOWING 2 SOILS TRANSPOSED FROM USDA TRIANGLE

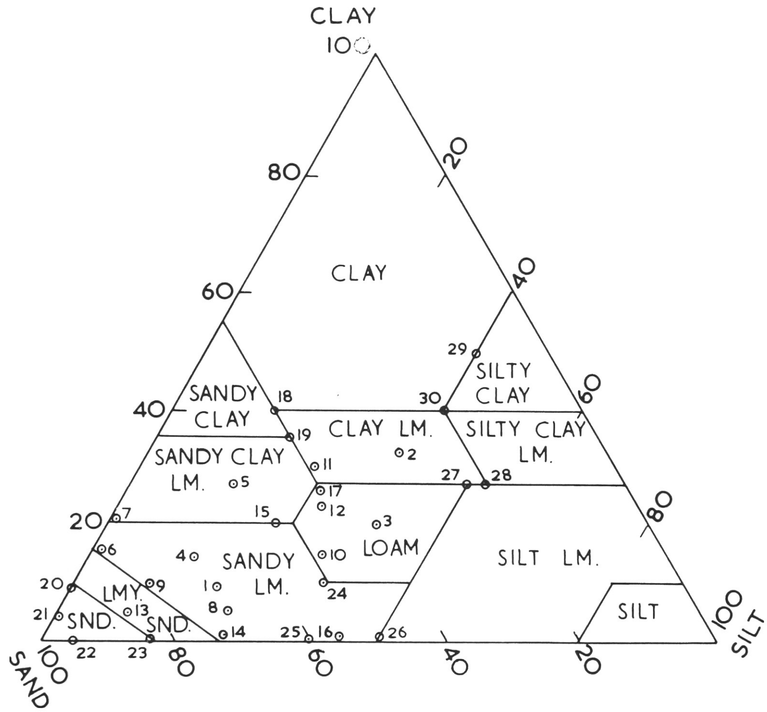


FIGURE 6 : USDA TEXTURAL CLASSIFICATION

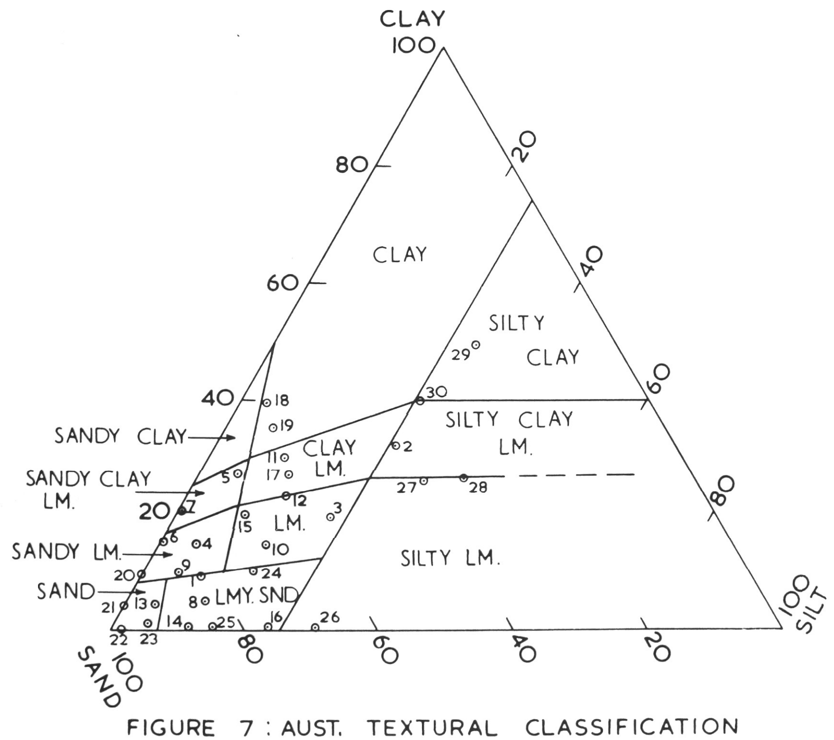


FIGURE 7 : AUST. TEXTURAL CLASSIFICATION

FIGURE 6 & 7 : COMPARISON OF THE USDA & AUST. CLASSIFICATION OF THIRTY SOILS

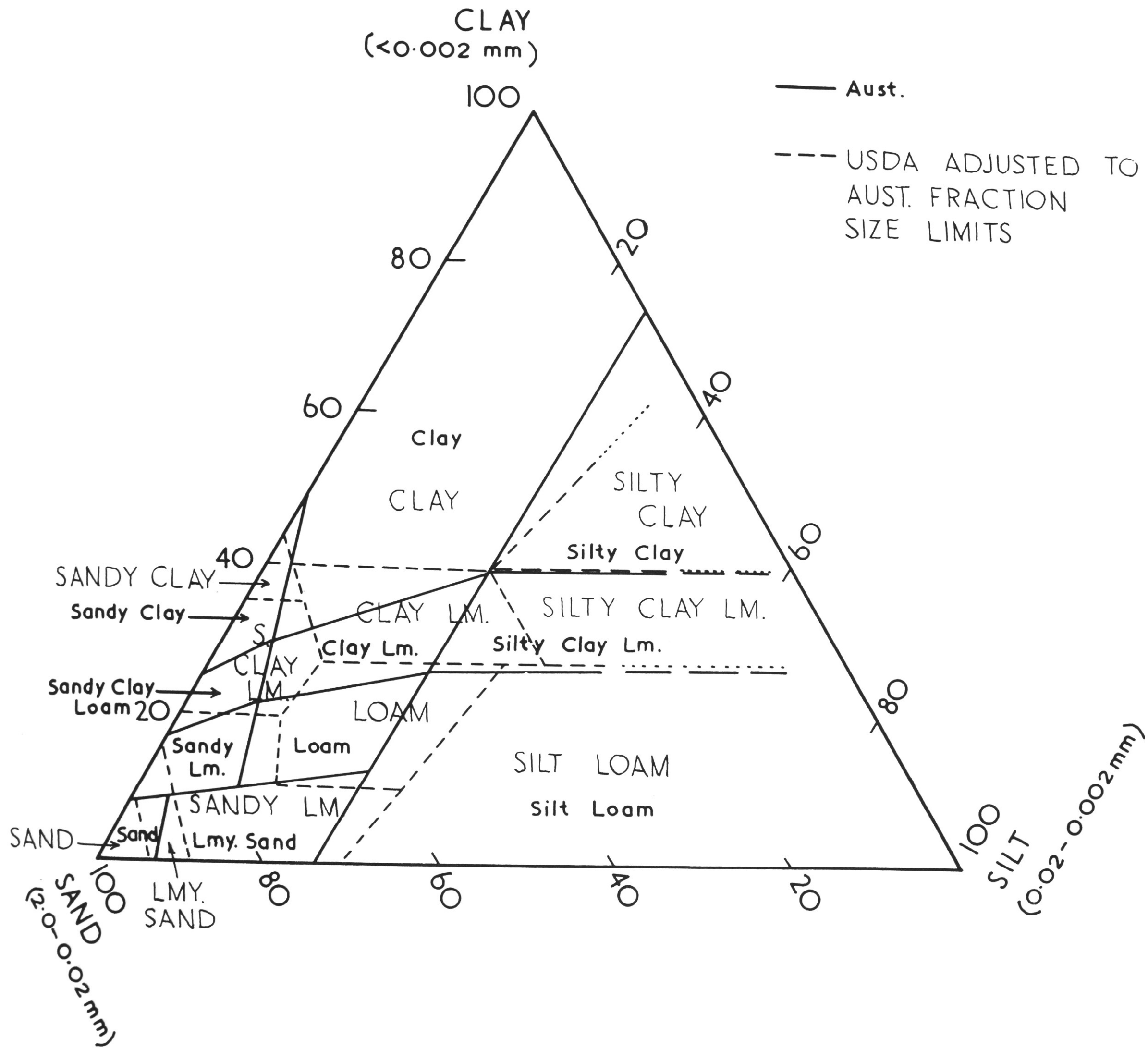


FIGURE 8 : AUST. TEXTURAL TRIANGLE SHOWING AUST. CLASS DIVISIONS & ALSO USDA DIVNS. ADJUSTED FOR THE AUST. FRACTION LIMITS

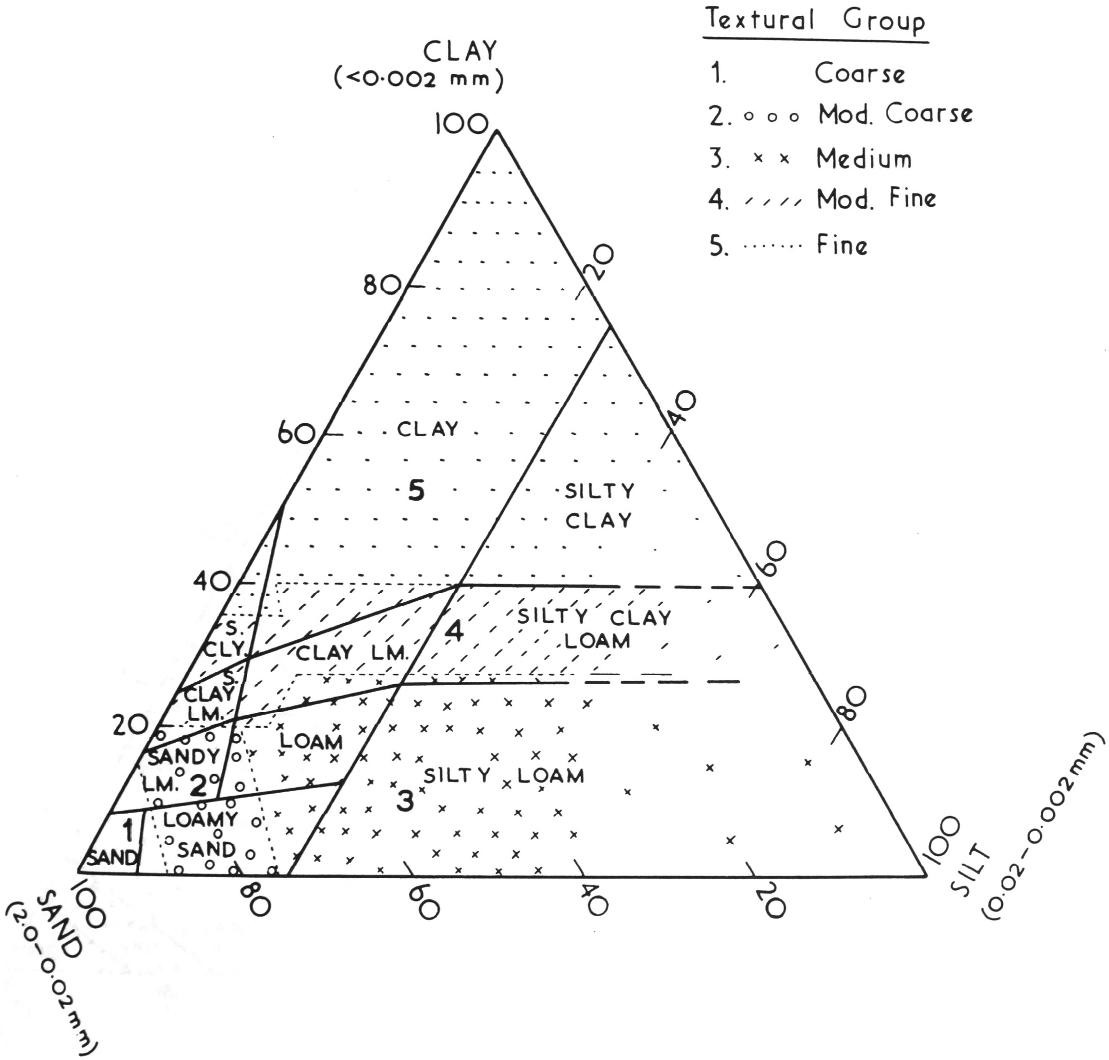


FIGURE 9: AUST. TEXTURAL CLASS TRIANGLE SHOWING USDA TEXTURAL GROUPS ADJUSTED FOR AUST. FRACTION LIMITS.

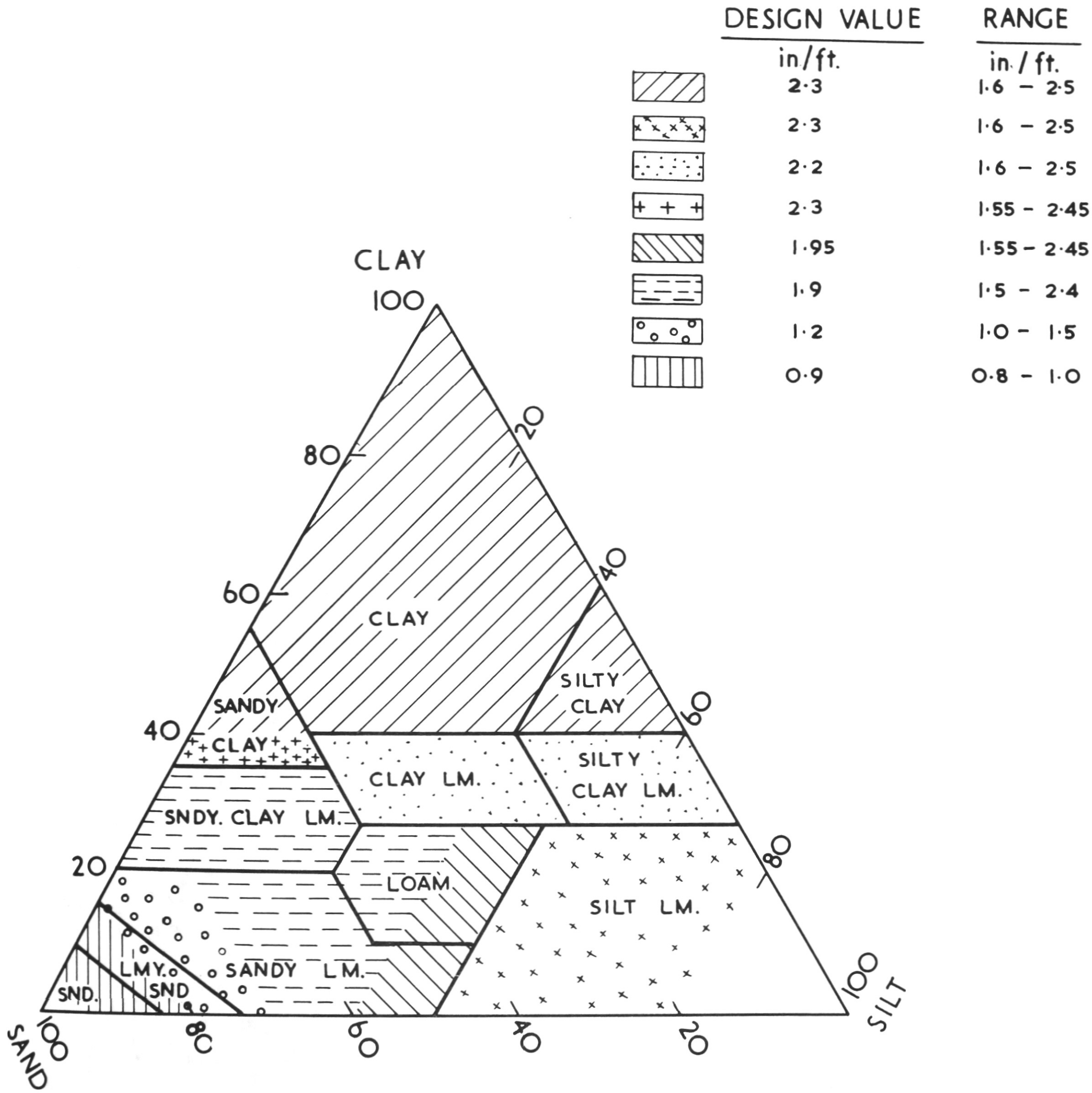


FIGURE 10: USDA TEXTURAL TRIANGLE SHOWING RANGES & DESIGN VALUES OF AVAILABLE WATER CAPACITY (From Shockley 1955)

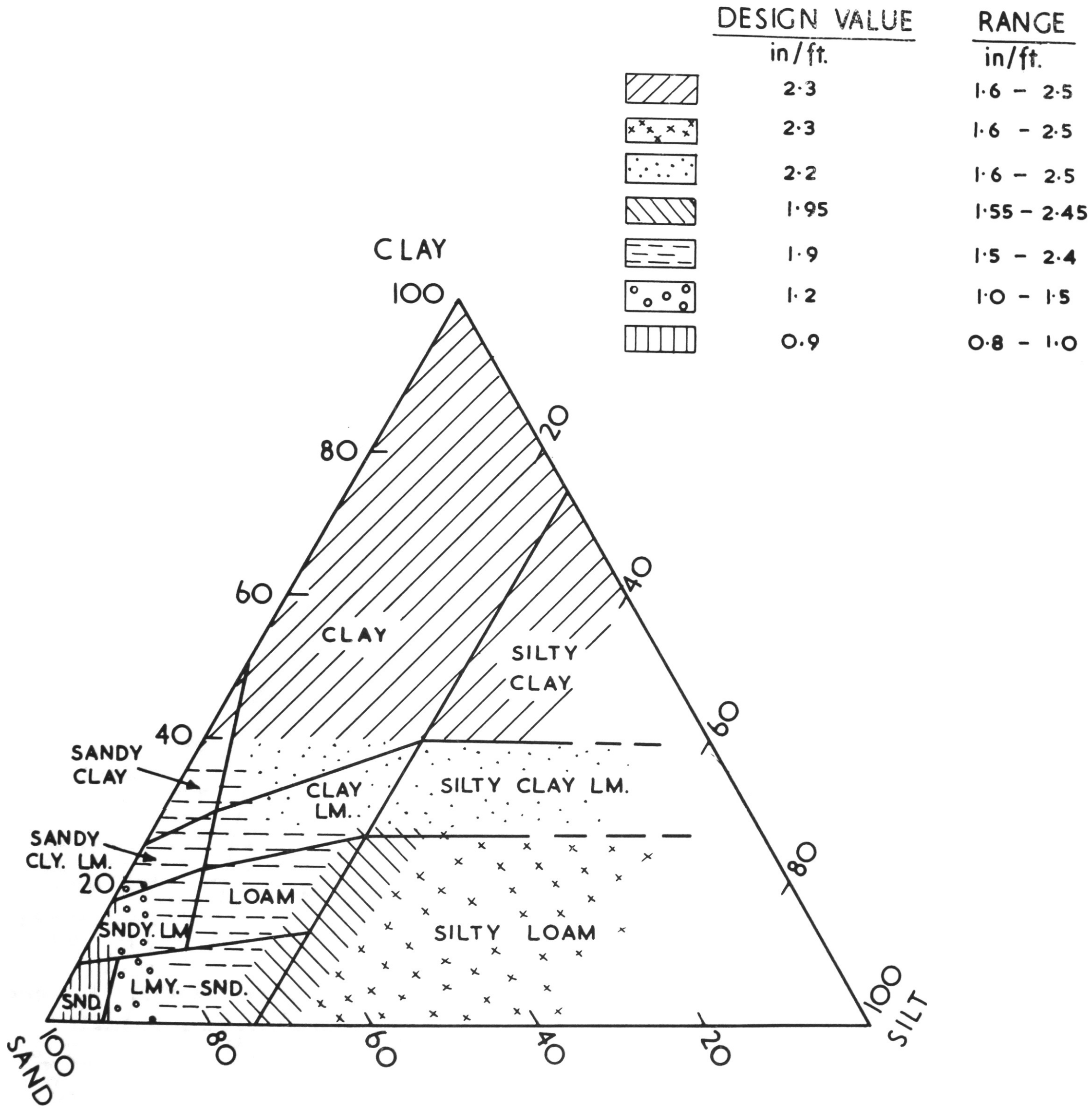


FIGURE 11: AUST. TEXTURAL TRIANGLE SHOWING AVAILABLE WATER CAPACITY DATA TRANSPOSED FROM FIGURE 10 & ADJUSTED FOR AUST. FRACTION LIMITS

SOIL	AWC, in/ft.	
	RANGE	DESIGN VALUE
A		1·7
B1	1·7 – 1·9	1·7
B2	1·9 – 2·1	2·0
B3	2·1 – 2·2	2·1
D	1·9 – 2·1	2·0
E1	1·5 – 1·8	1·7
E2	1·1 – 1·5	1·3
F1	0·8 – 1·1	0·9
F2	UP TO 0·8	0·6

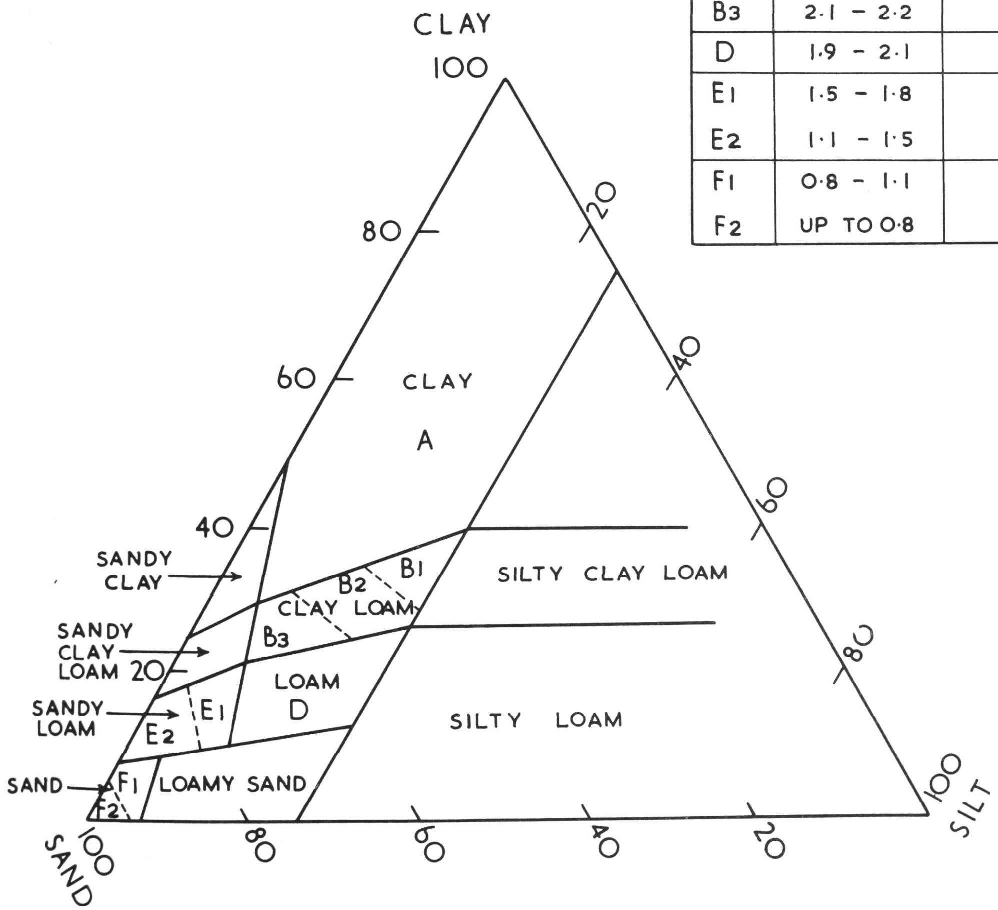


FIGURE 12: AUST. TEXTURAL TRIANGLE SHOWING AVAILABLE WATER CAPACITY DATA FROM DRAFT AUST. SPRAY IRRIGATION CODE

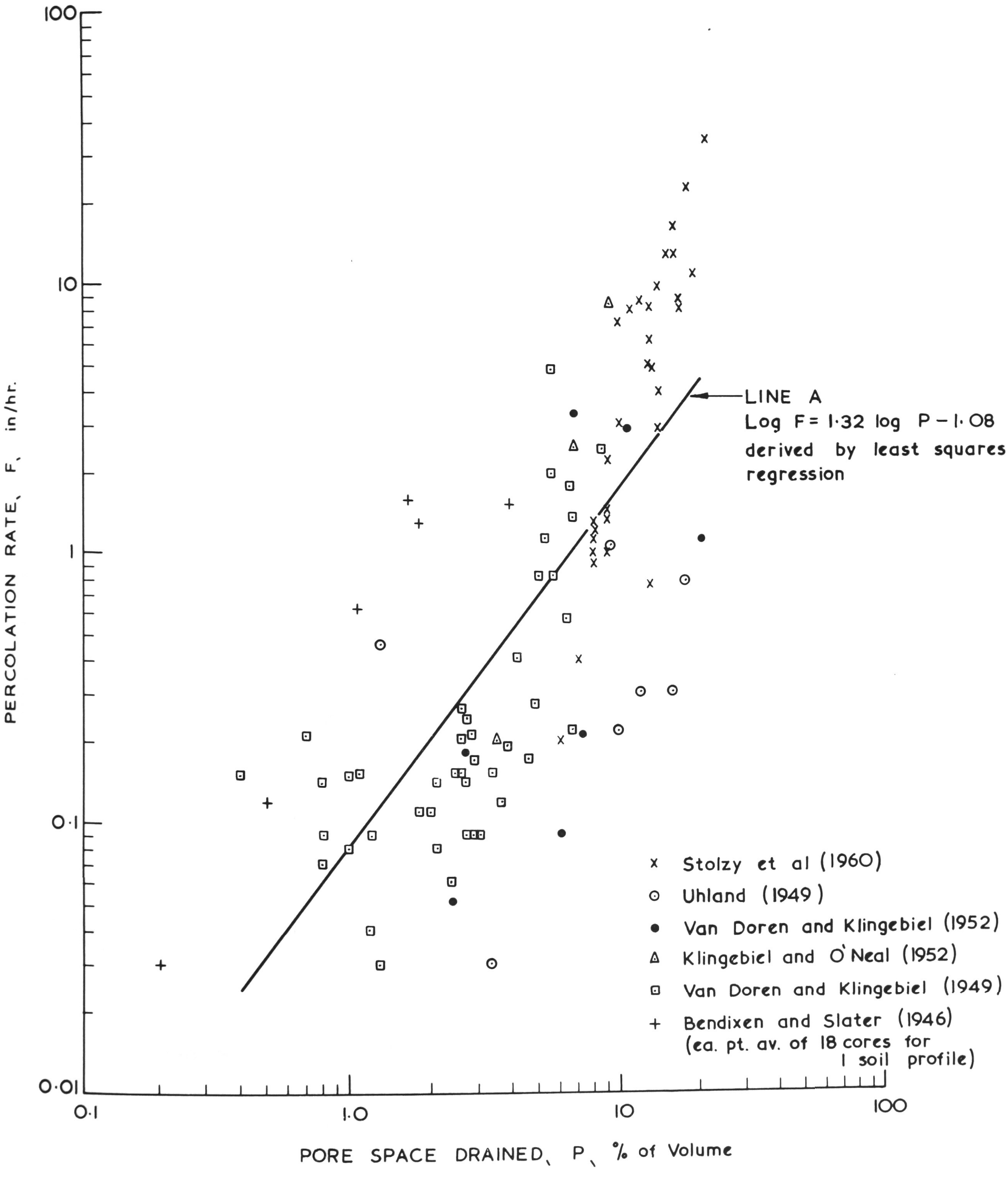


FIGURE 13: CORRELATION OF PERCOLATION RATE AND PORE SPACE DRAINED

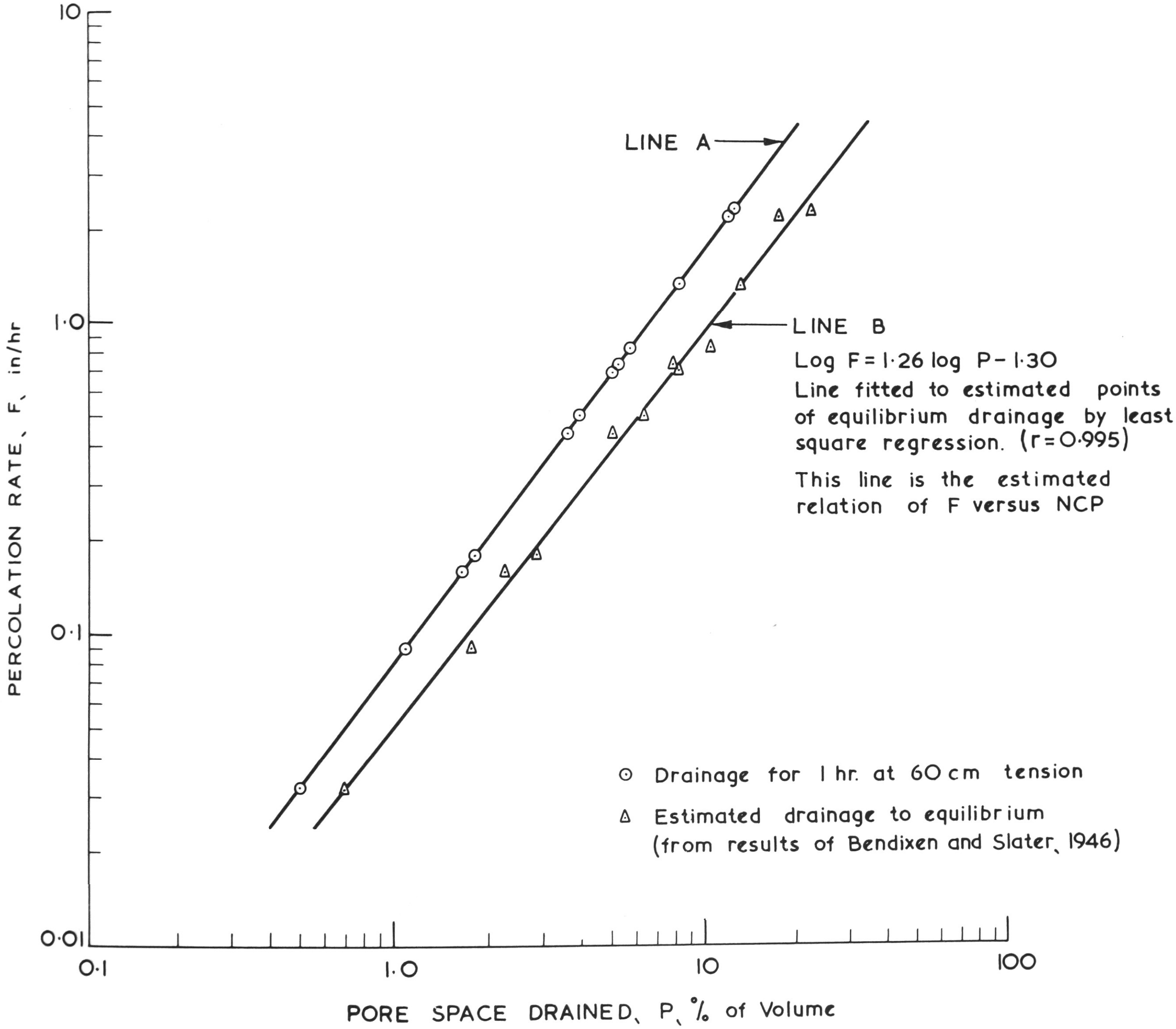


FIGURE 14: ESTIMATION OF RELATIONSHIP BETWEEN PERCOLATION RATE AND PORE SPACE DRAINED AT EQUILIBRIUM

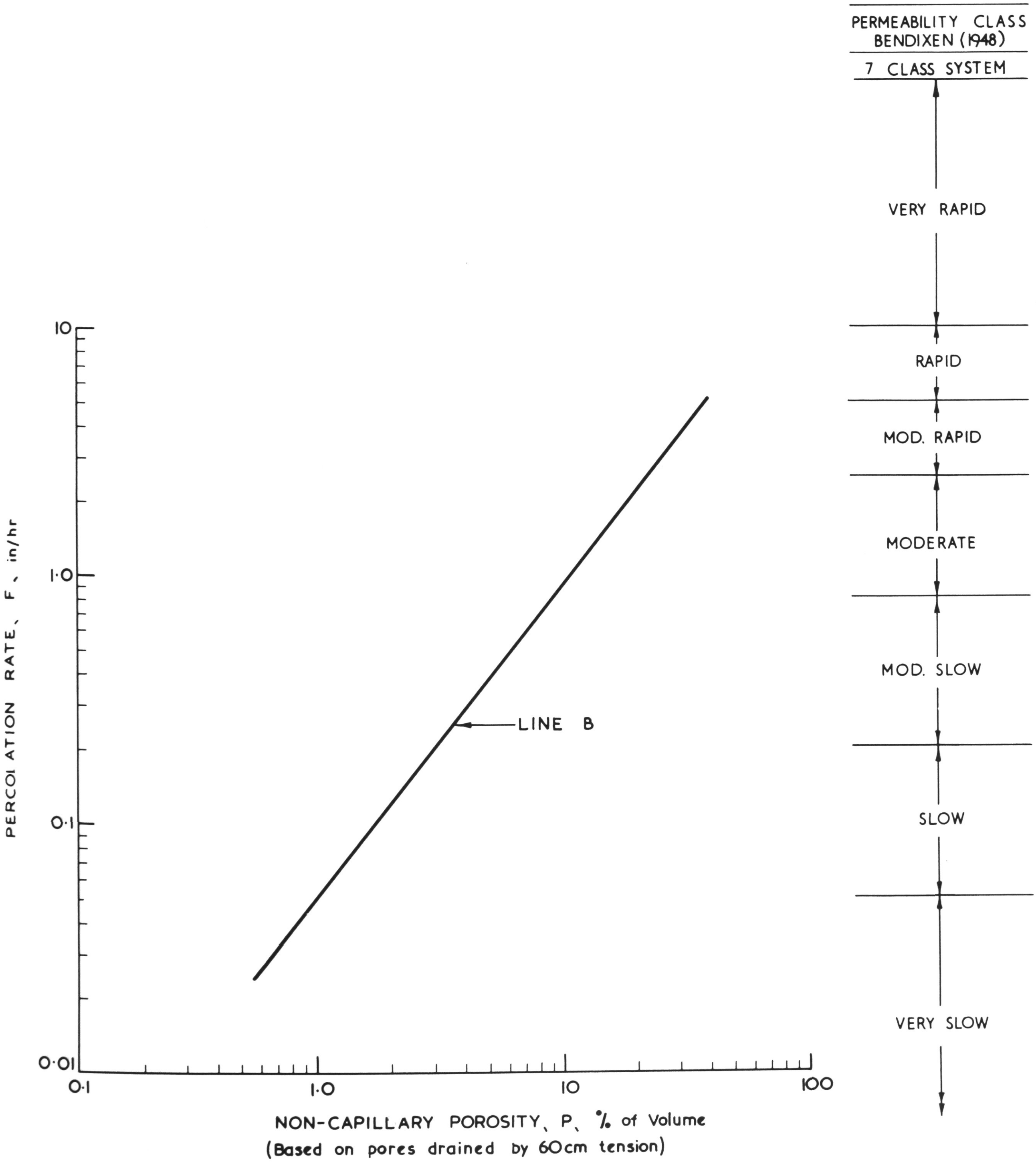


FIGURE 15: ESTIMATED RELATION BETWEEN NCP & PERMEABILITY CLASSIFICATION

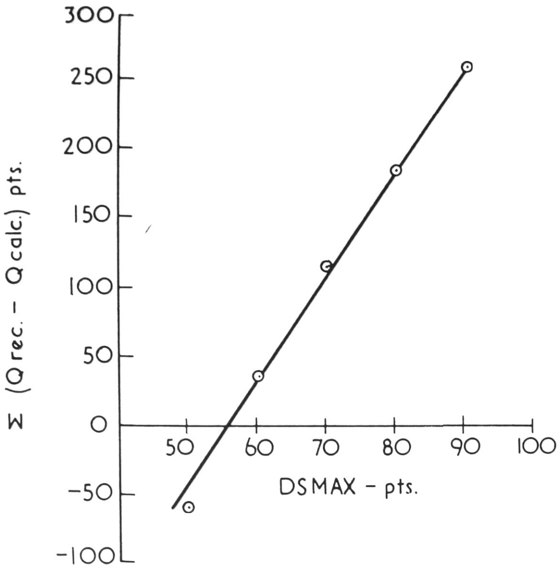


FIGURE 16

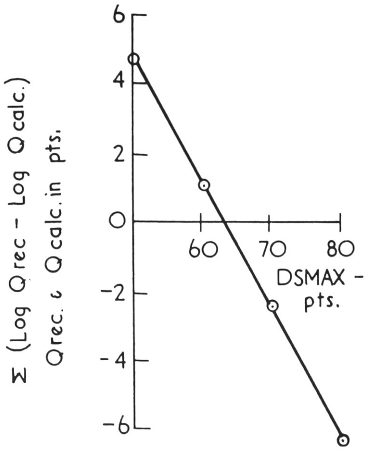


FIGURE 17

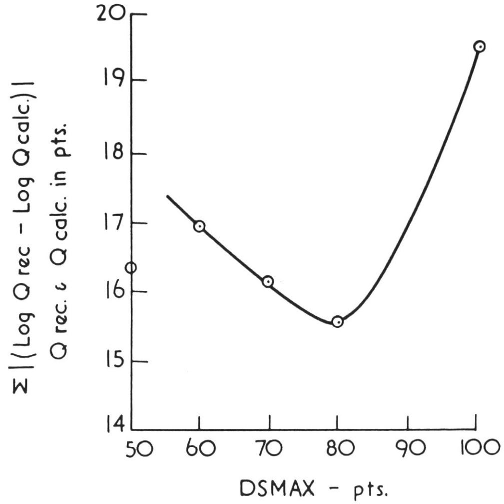


FIGURE 18

FIGURES 16, 17 & 18: BADGERYS CREEK − OPTIMISATION OF DSMAX

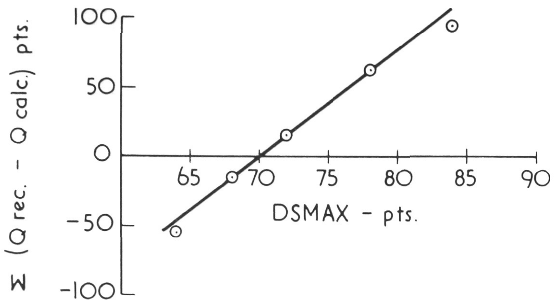


FIGURE 19.

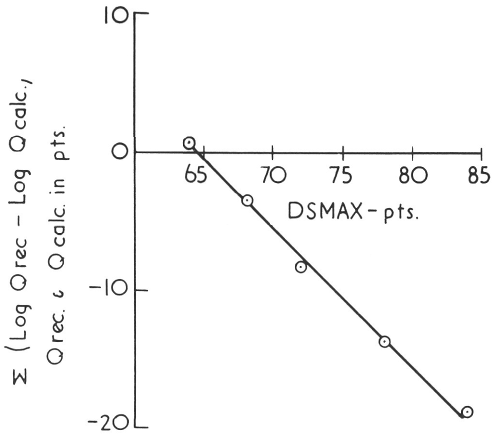


FIGURE 20.

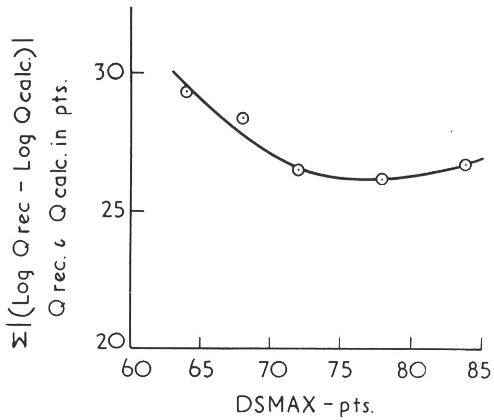


FIGURE 21.

FIGURES 19, 20 & 21: SCONE - OPTIMISATION OF DSMAX

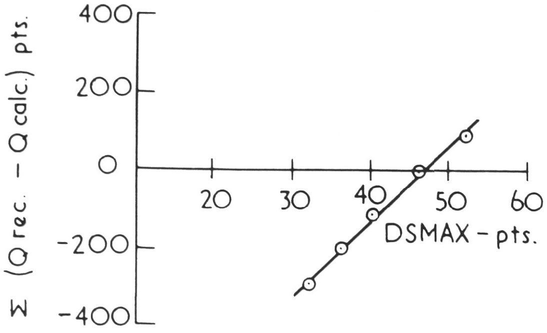


FIGURE 22

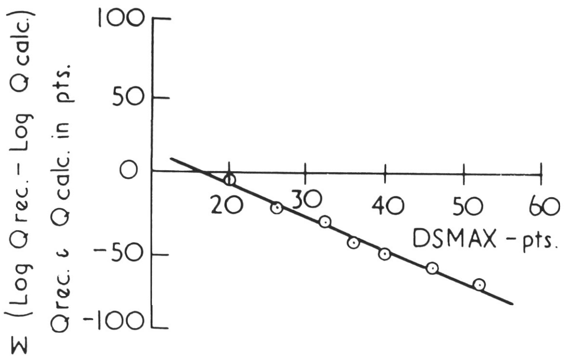


FIGURE 23

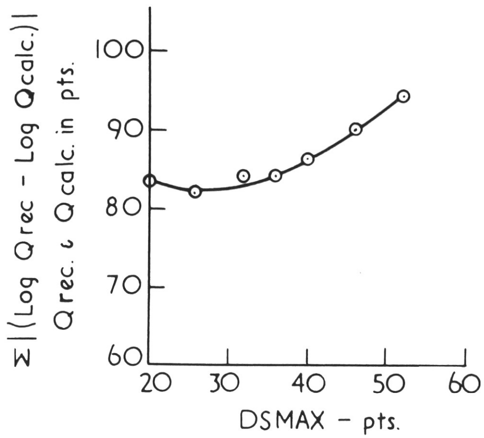


FIGURE 24

FIGURES 22, 23 & 24: WAGGA WAGGA − OPTIMISATION OF DSMAX

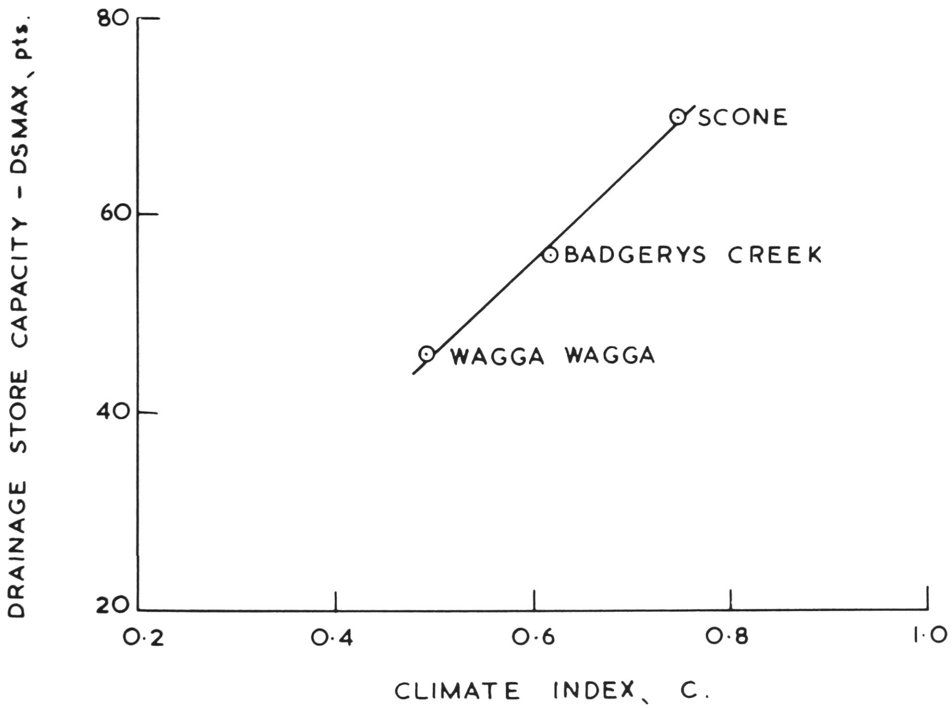


FIGURE 25: CORRELATION BETWEEN DSMAX AND CLIMATE INDEX (C)

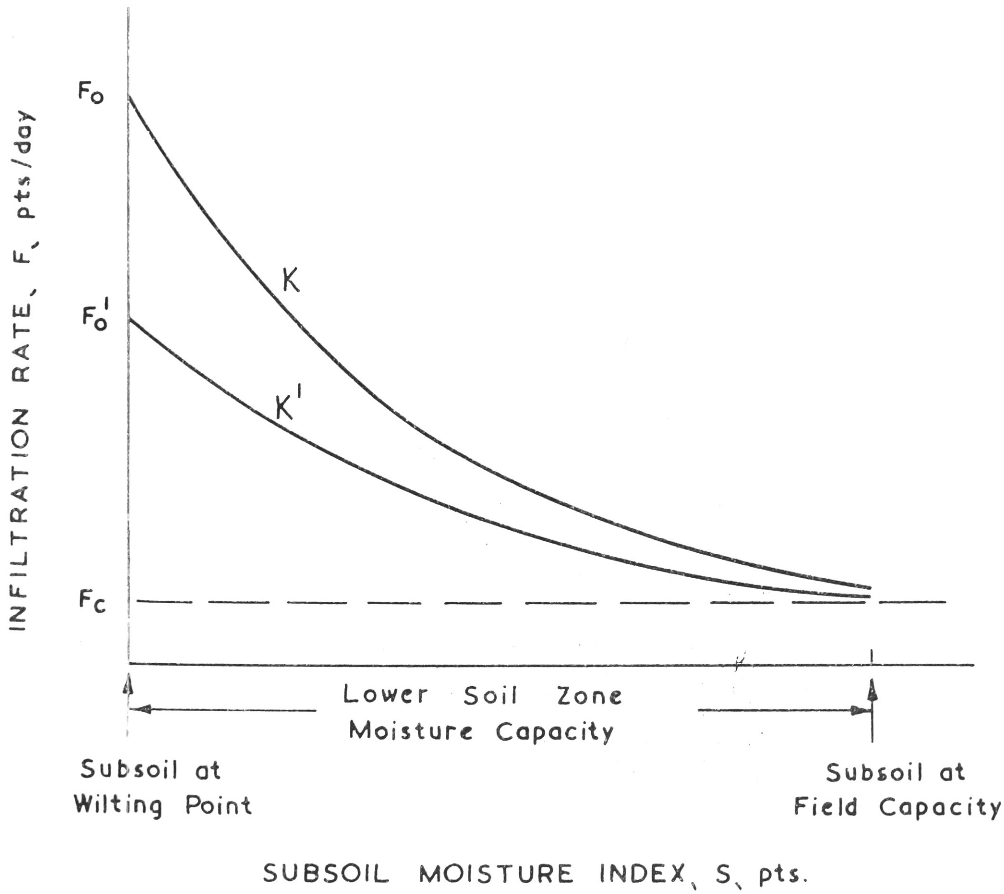


Figure 26: Infiltration Equation

$$F = F_o + (F_o - F_c)e^{-KS}$$

LEGEND	TEXTURE	REMARKS	SOURCE
⊡	SILT LOAM	INITIALLY DRY, 5" HEAD	LETEY ET AL (1961)
■	SANDY LOAM	INITIALLY DRY	BODMAN & COLMAN (1943)
⊕	SILT LOAM		
--■--	SANDY LOAM	INITIALLY WET	BODMAN & COLMAN (1944)
--⊗--	SILT LOAM		
✕	SANDY LOAM	INITIALLY DRY	MILLER & RICHARD (1952)
⊙	SANDY LOAM		
●	SILT CLAY LOAM		
Δ	SILTY CLAY LOAM	INITIALLY DRY, HOR. INFILTRATION	KIRKHAM & FENG (1948)
▲	SILT LOAM		
⊠ F	SOUTH AUST. CLAY	INITIALLY DRY, FLOODED	MARSHALL & STIRK (1949)
⊠ S	SOUTH AUST. CLAY	INITIALLY DRY, SPRINKLED	
x	LIGHT CLAY	INITIAL MOISTURE CONTENT (θ) VARIED FROM DRY (θ=O) TO SATURATED (θ = O·495)	PHILIP (5, 1957)

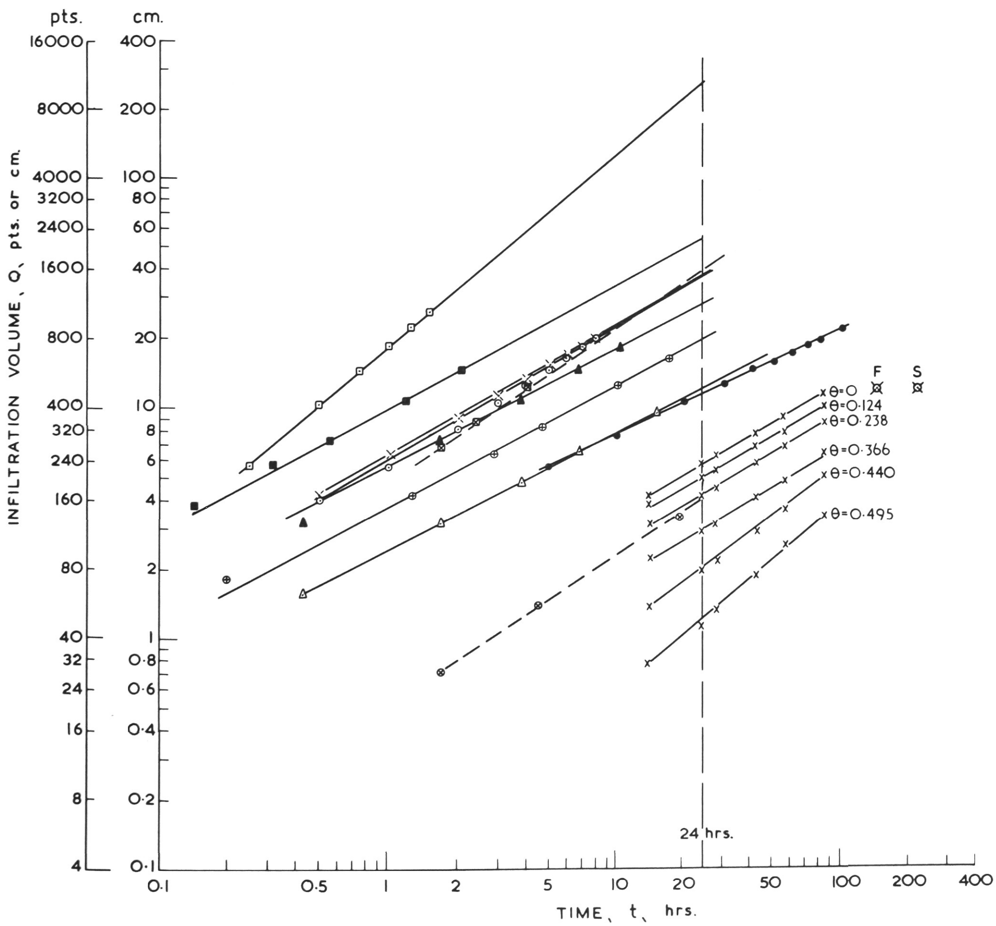


FIGURE 27: INFILTRATION VOLUME VERSUS TIME RELATIONSHIPS FOR SOILS OF VARIOUS TEXTURES

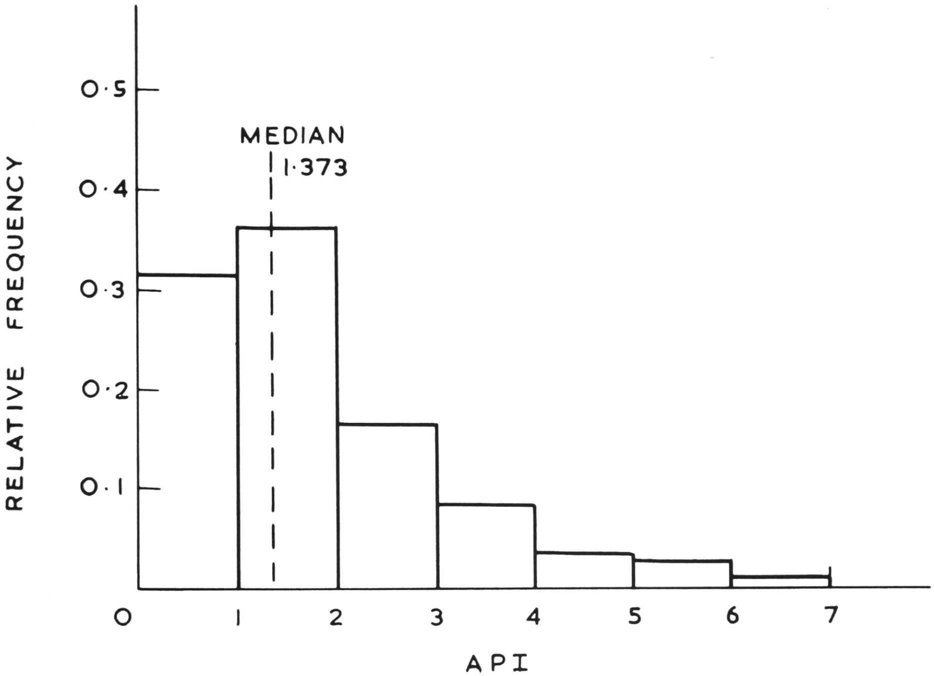


FIGURE 28: API RELATIVE FREQUENCY DIAGRAM

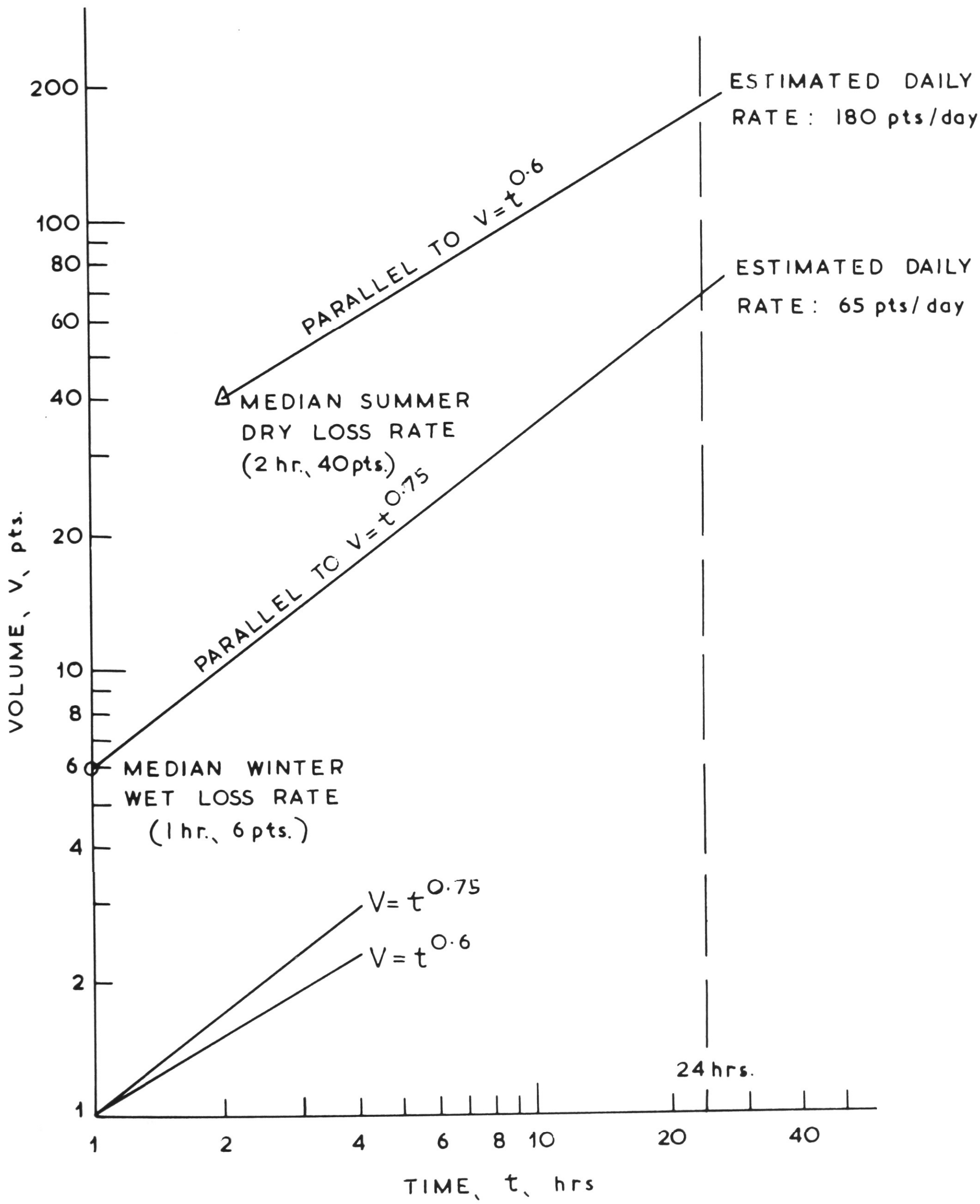


FIGURE 29: ESTIMATION OF DAILY VOLUME OF INFILTRATION FROM MEDIAN LOSS RATE

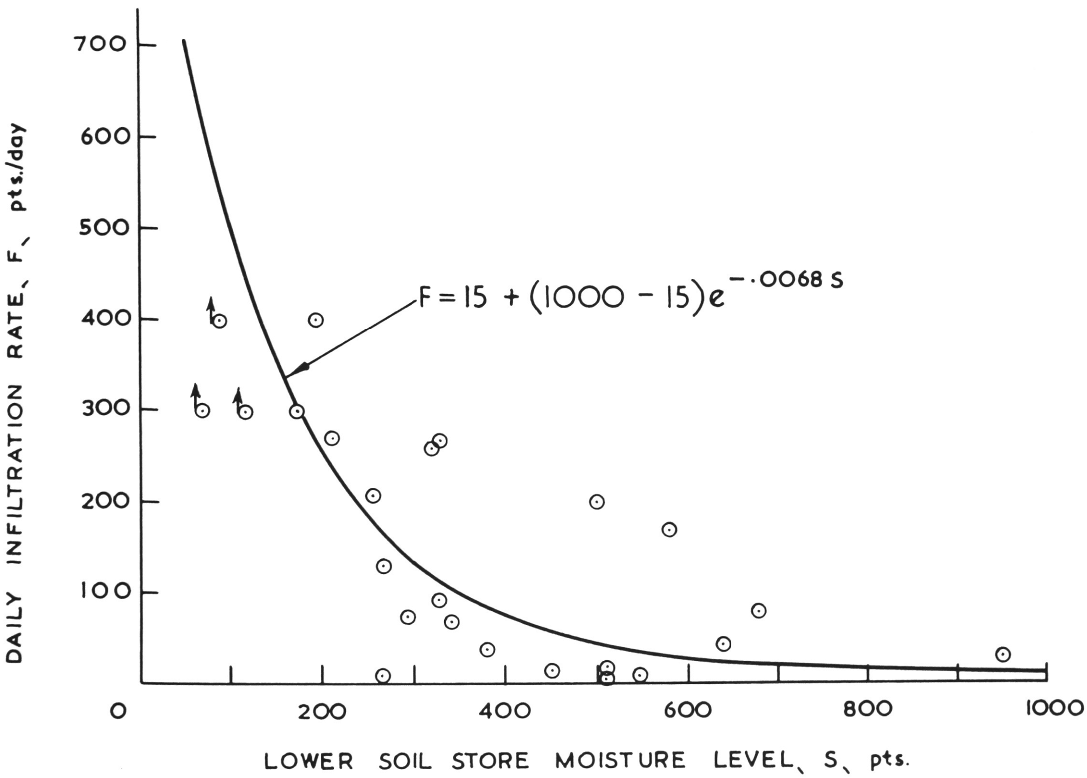


FIGURE 30: SCONE - DERIVATION OF INFILTRATION CURVE BY TRIAL & ERROR USING THE COMPUTER

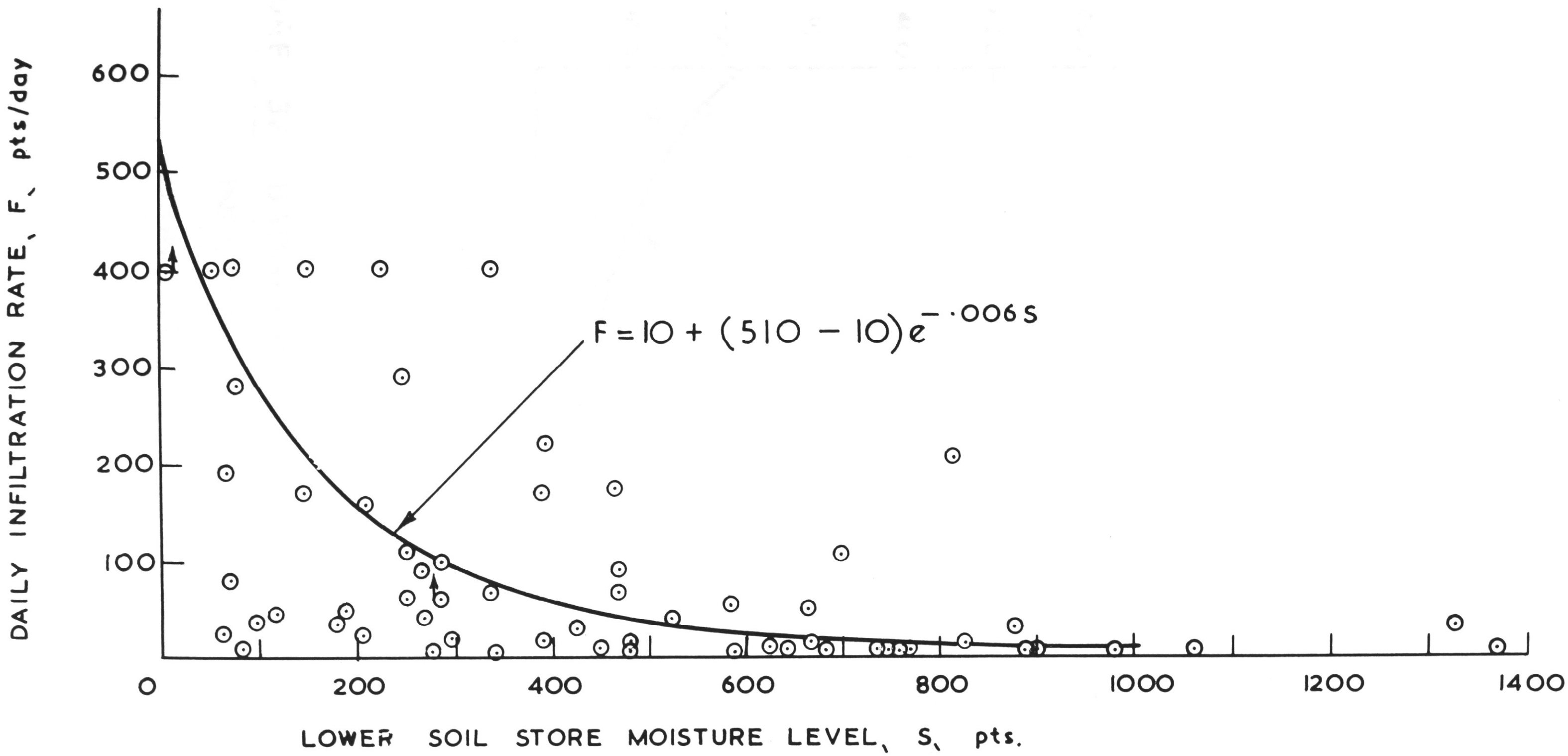


FIGURE 31: WAGGA WAGGA – DERIVATION OF INFILTRATION CURVE BY TRIAL & ERROR USING THE COMPUTER

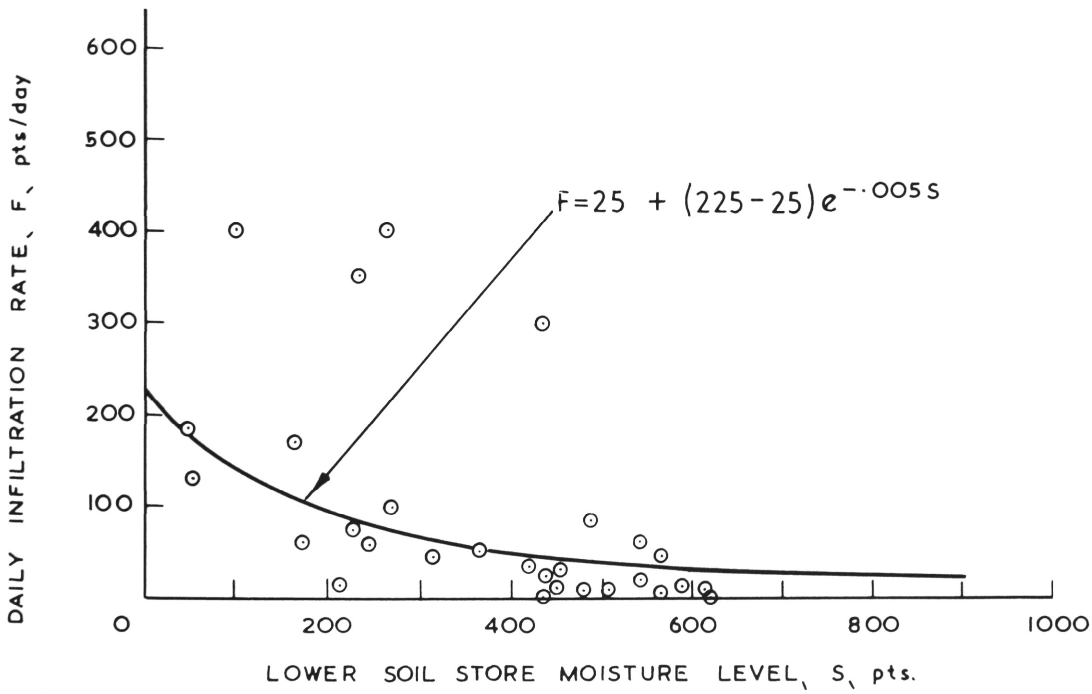


FIGURE 32: BADGERYS CREEK – DERIVATION OF INFILTRATION CURVE BY TRIAL & ERROR USING THE COMPUTER

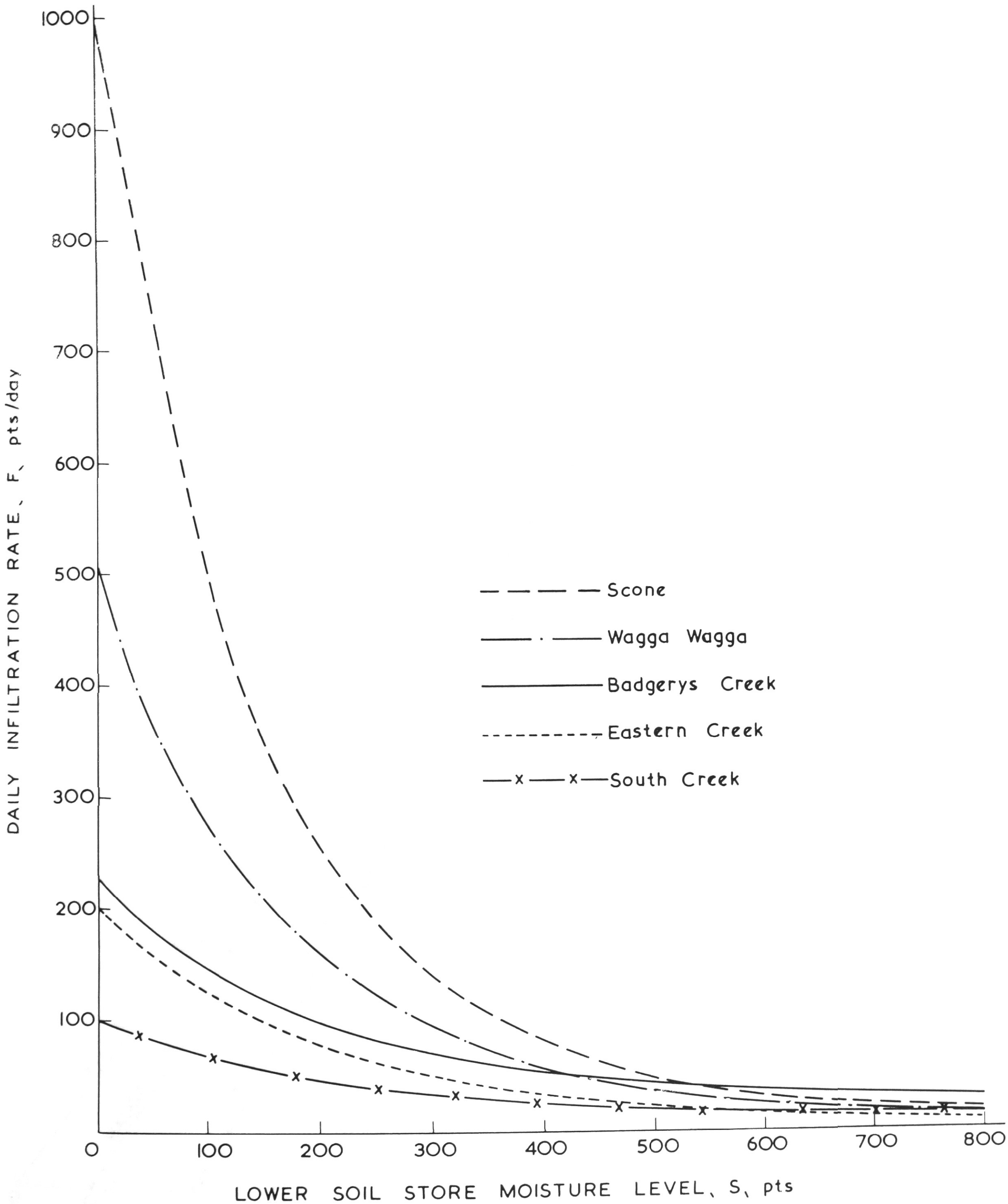


FIGURE 33: INFILTRATION CURVES DERIVED BY TRIAL AND ERROR USING THE COMPUTER

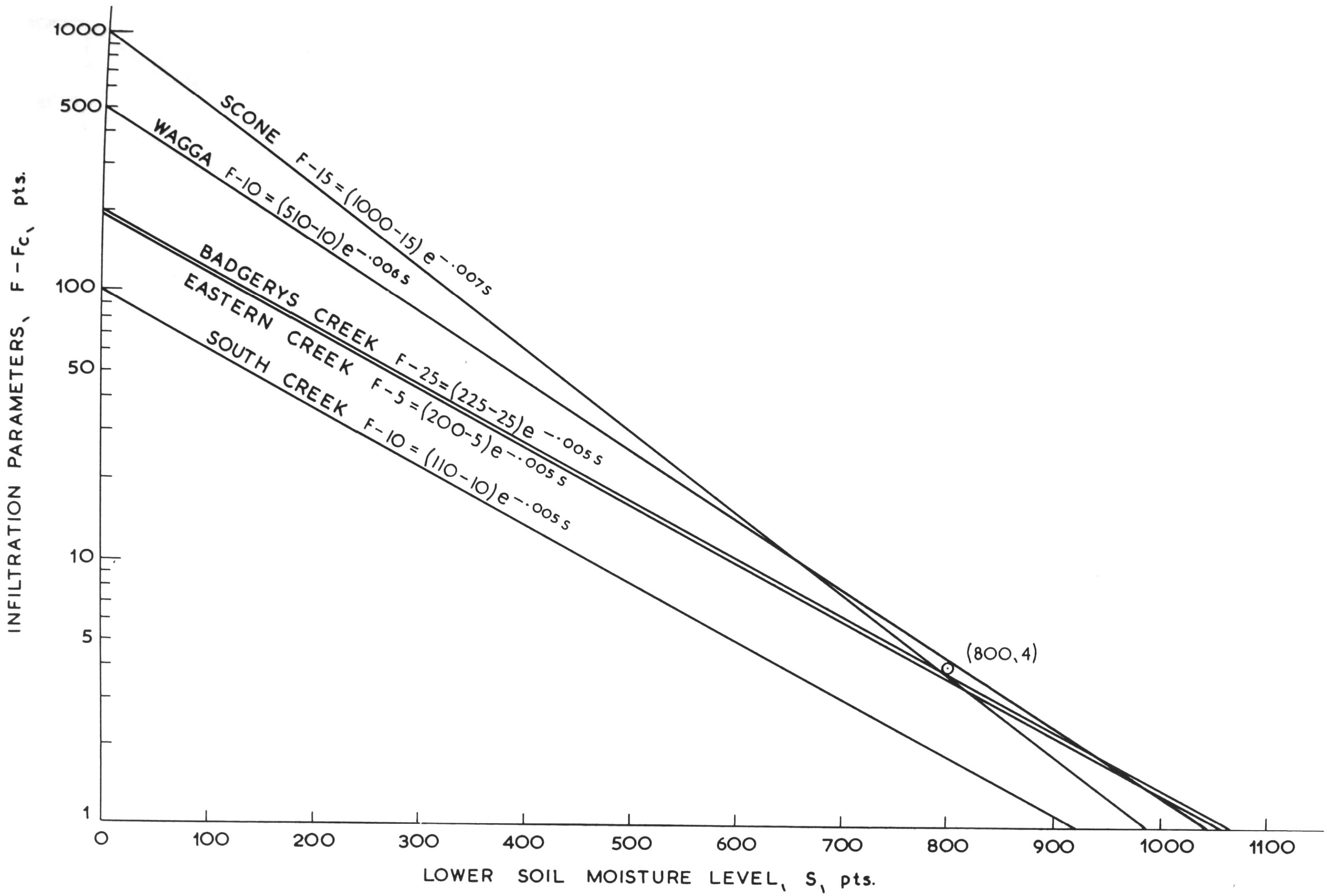


FIGURE 34: DERIVED INFILTRATION CURVES WITH EQUATIONS $F = F_c + (F_0 - F_c)e^{-KS}$

PLOTTED IN THE FORM $F - F_c$ VERSUS S

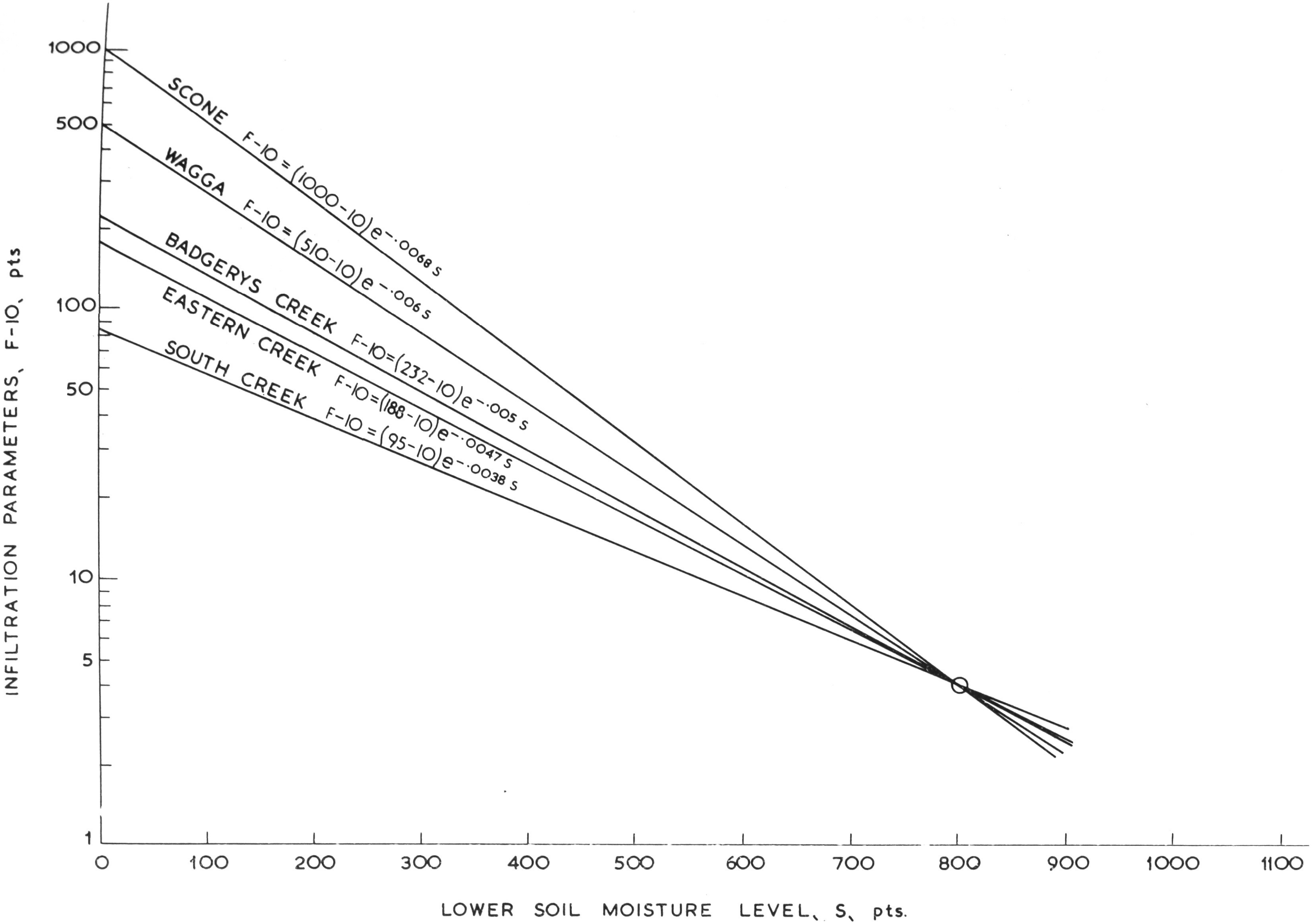


Figure 35: Curves of the form $F=10+(F_0-10)e^{-KS}$ passing through the point (800 4) and of best fit to derived infiltration curves.

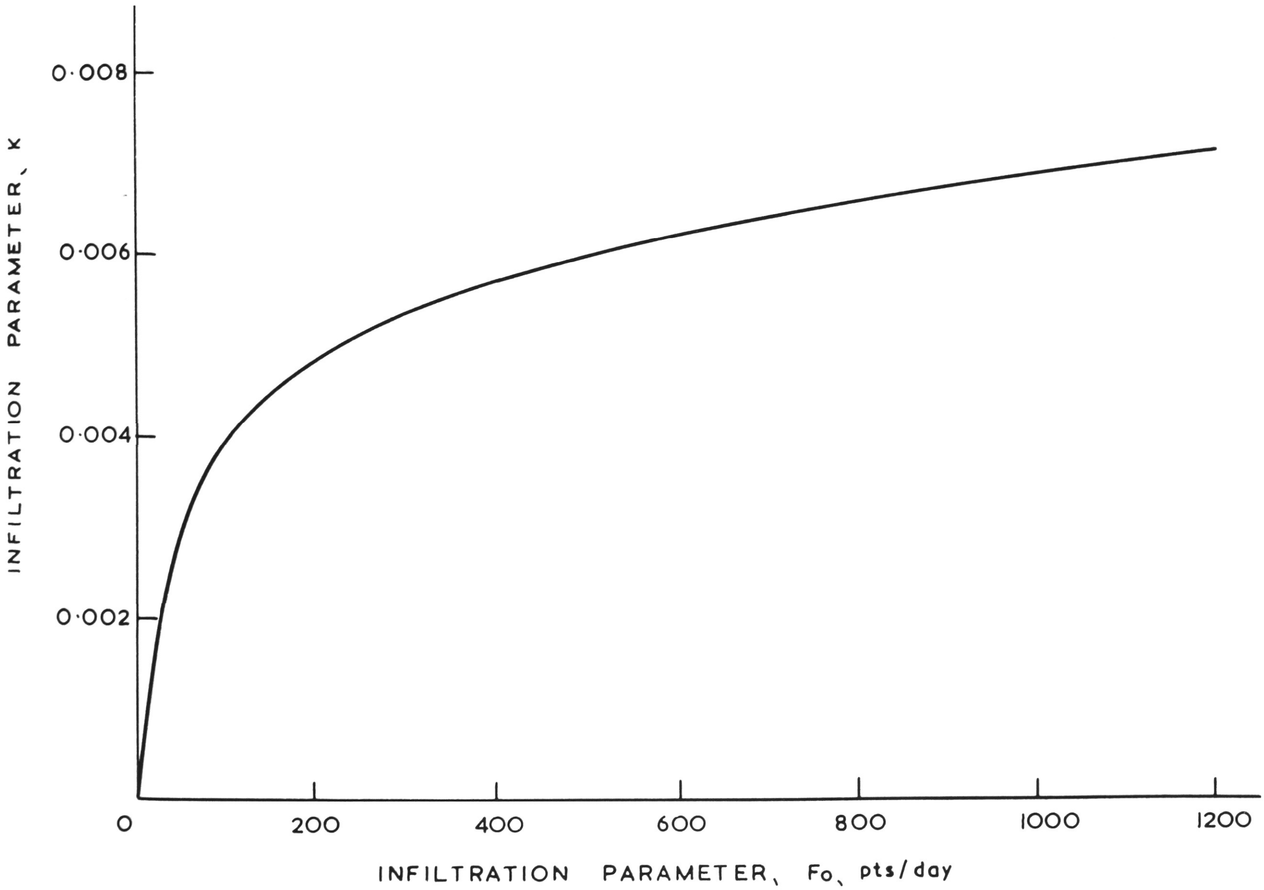


FIGURE 36: RELATIONSHIP BETWEEN K AND F_o FOR THE INFILTRATION CURVES $F = 10 + (F_o - 10)e^{-KS}$ TO PASS THROUGH THE POINT (800, 14)

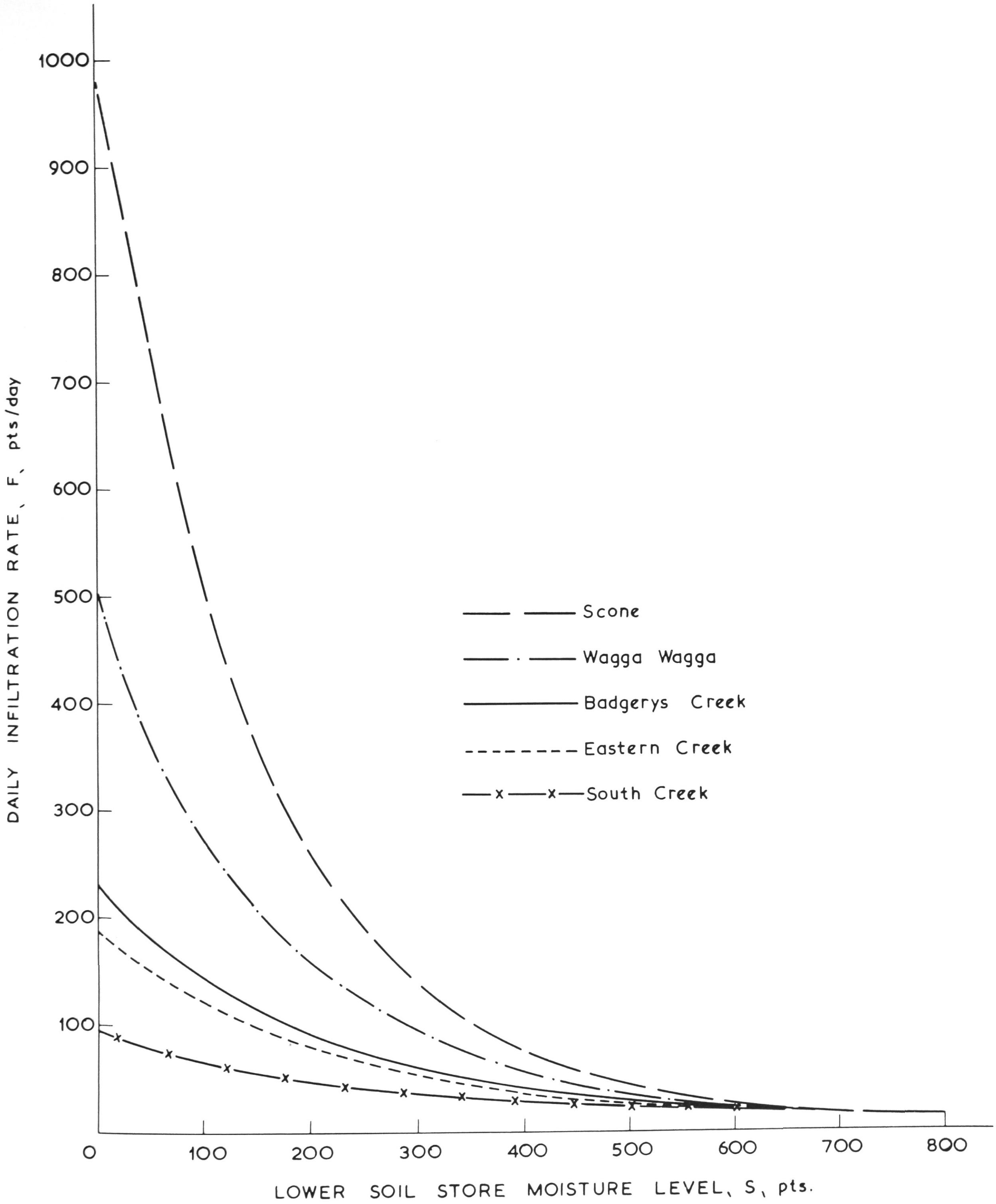


FIGURE 37: DERIVED INFILTRATION CURVES ADJUSTED TO PASS THROUGH (800, 14) AND IN FORM OF EQUATION $F = 10 + (F_0 - 10)e^{-KS}$

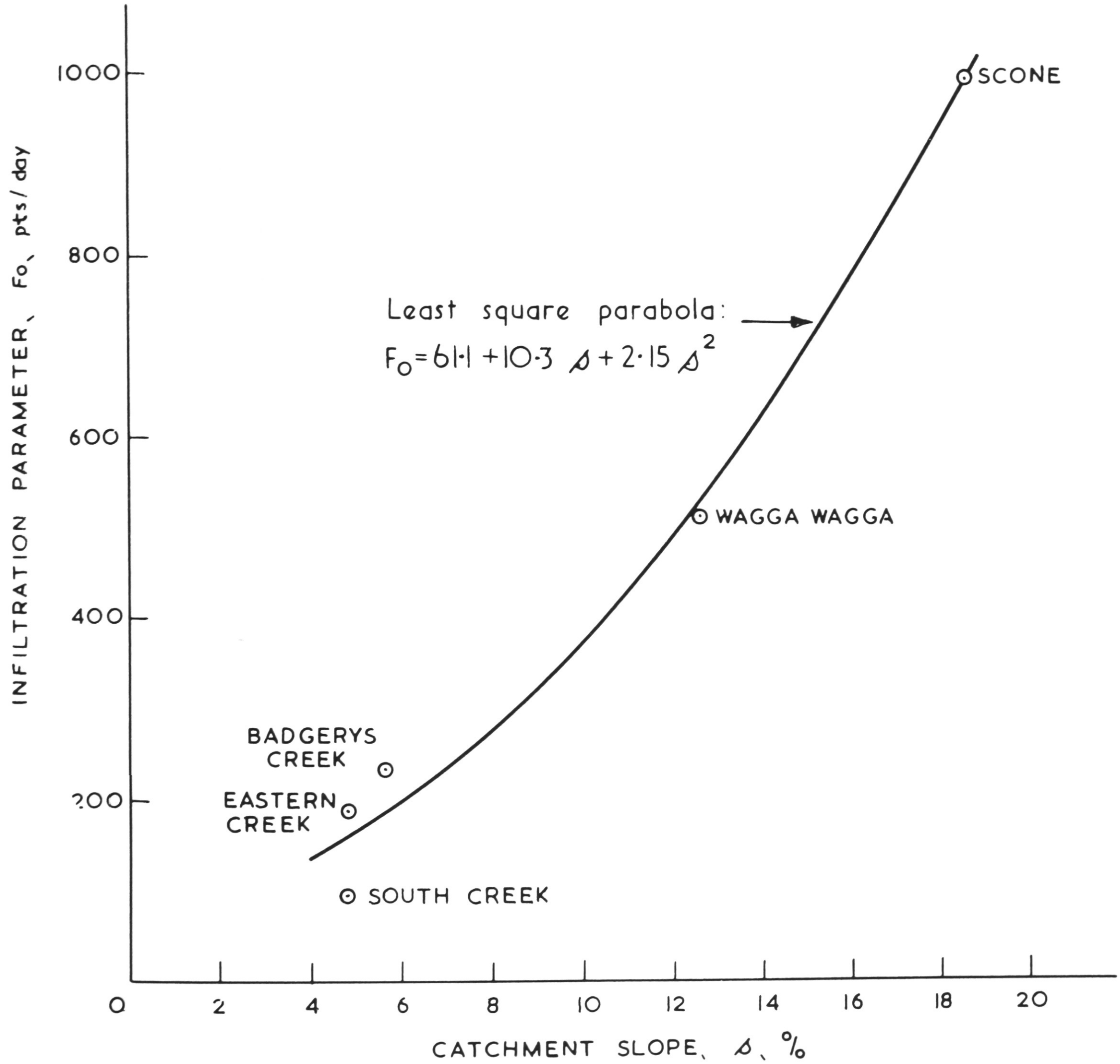


FIGURE 38: DERIVED RELATIONSHIP BETWEEN F_o AND ϕ

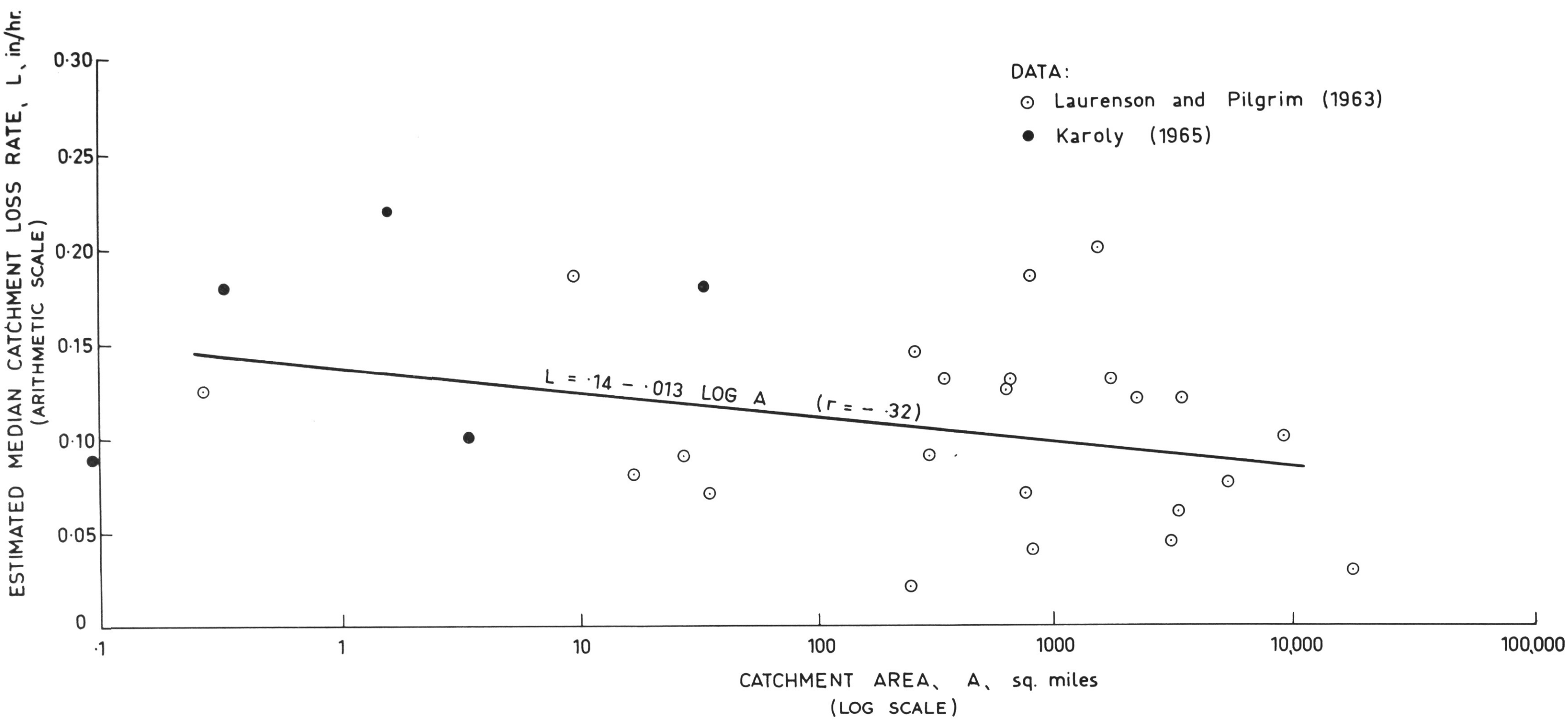


FIGURE 39: CORRELATION BETWEEN MEDIAN CATCHMENT LOSS RATE AND CATCHMENT AREA FOR AUSTRALIAN CATCHMENTS.

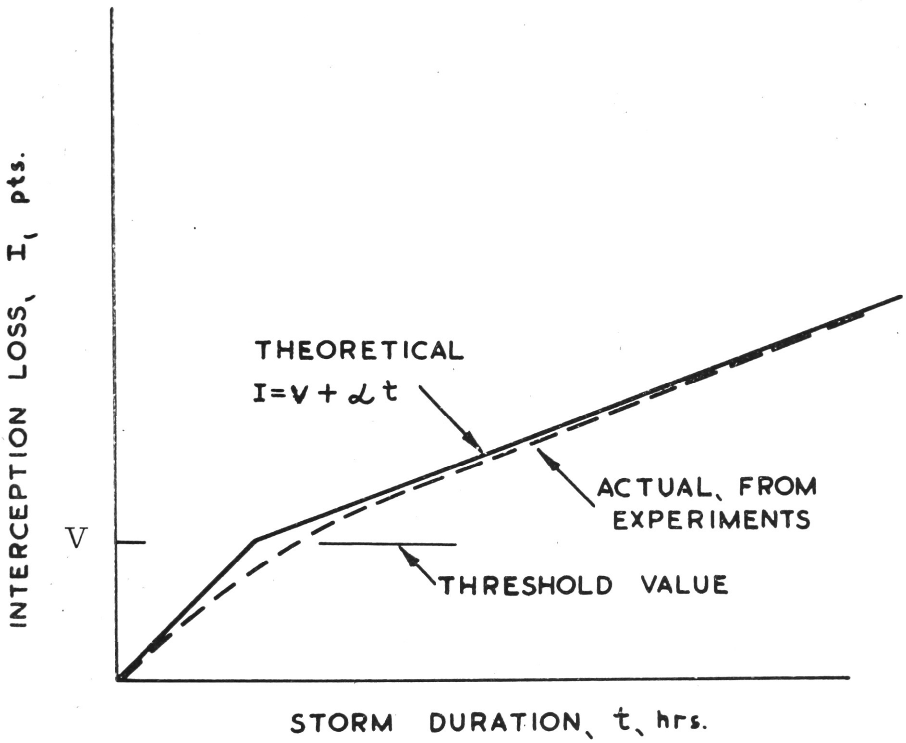


FIGURE 40: THE COMPONENTS OF INTERCEPTION LOSS

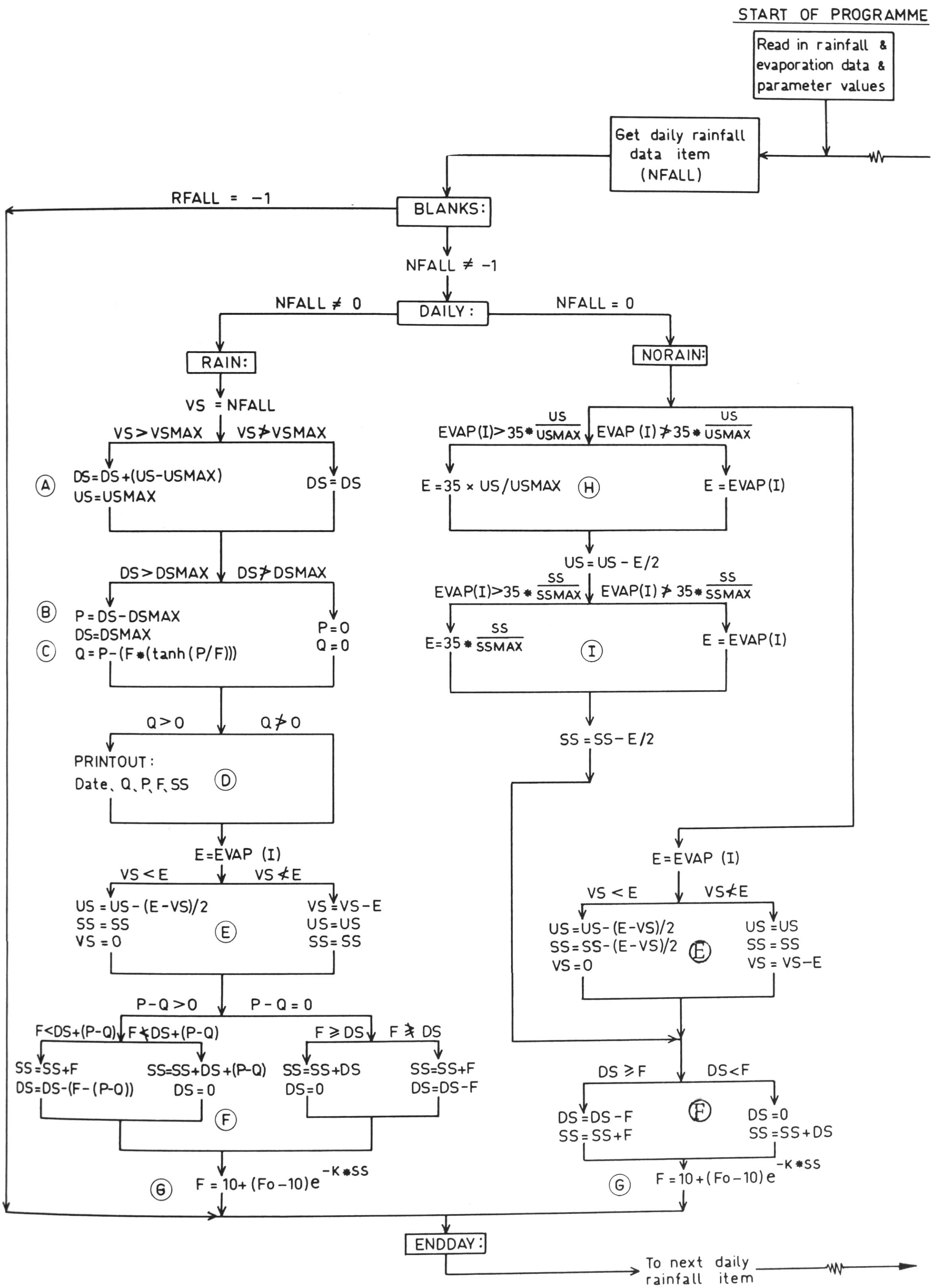


FIGURE 41: MODEL CALCULATIONS - PRESENTED DIAGRAMMATICALLY

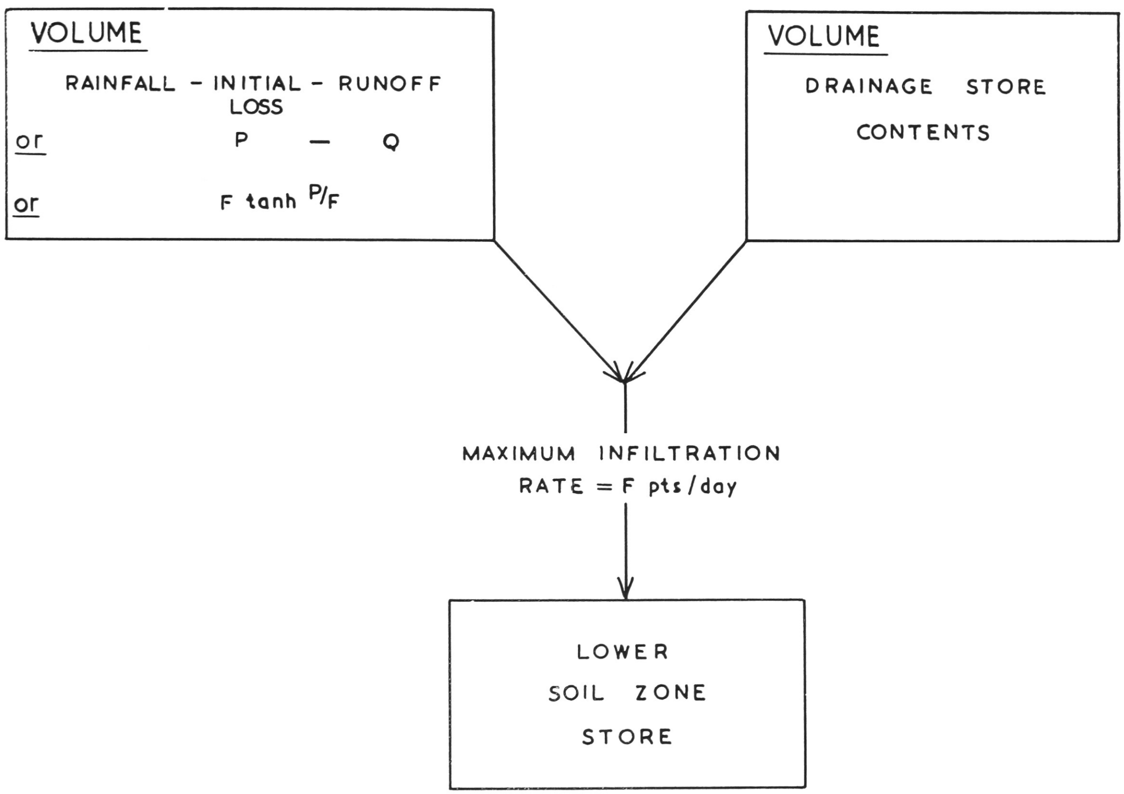


FIGURE 42: DAILY INFILTRATION OPERATION OF MODEL ILLUSTRATED SCHEMATICALLY

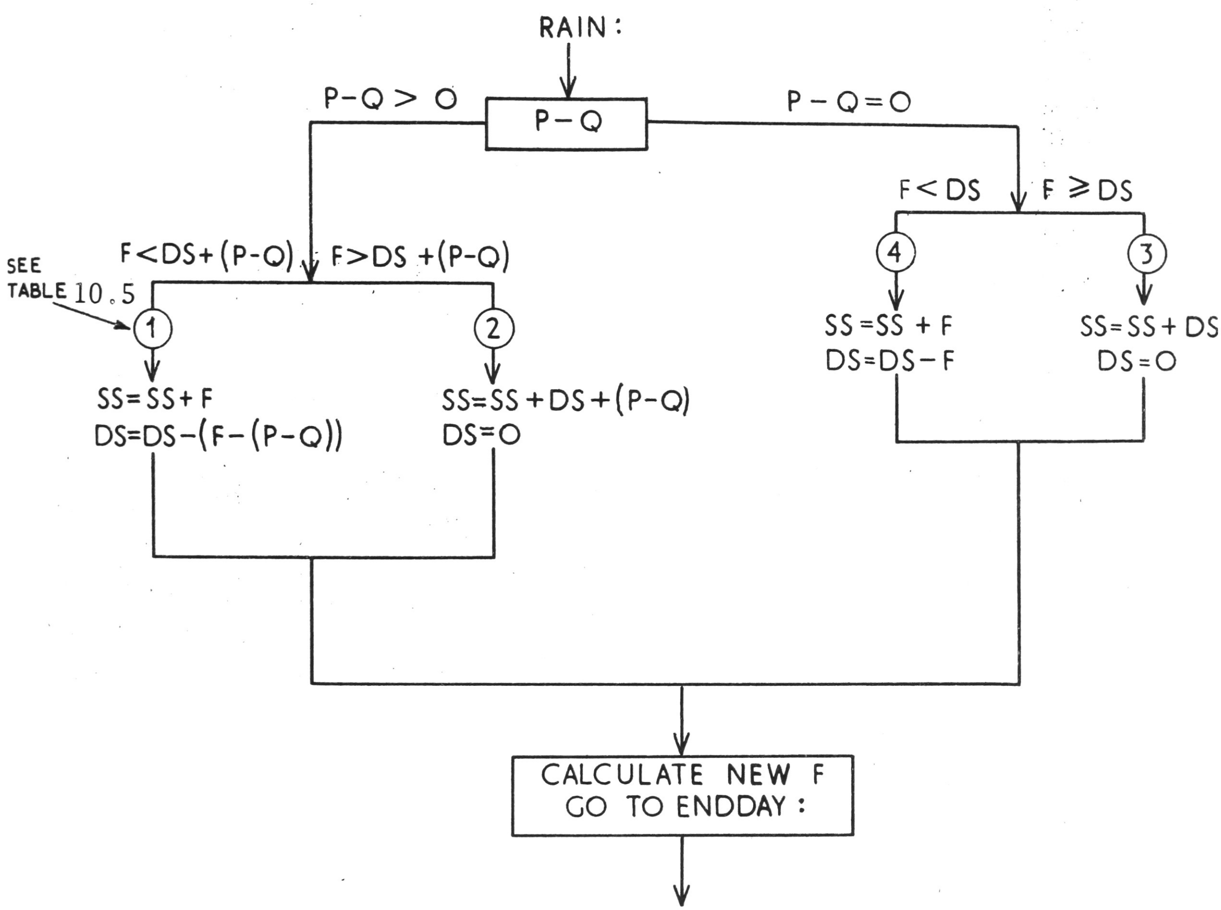


Figure 43: Infiltration Calculations for "Rain" Section of Model in Diagram Form (see also Tables 10.4 and 10.5).

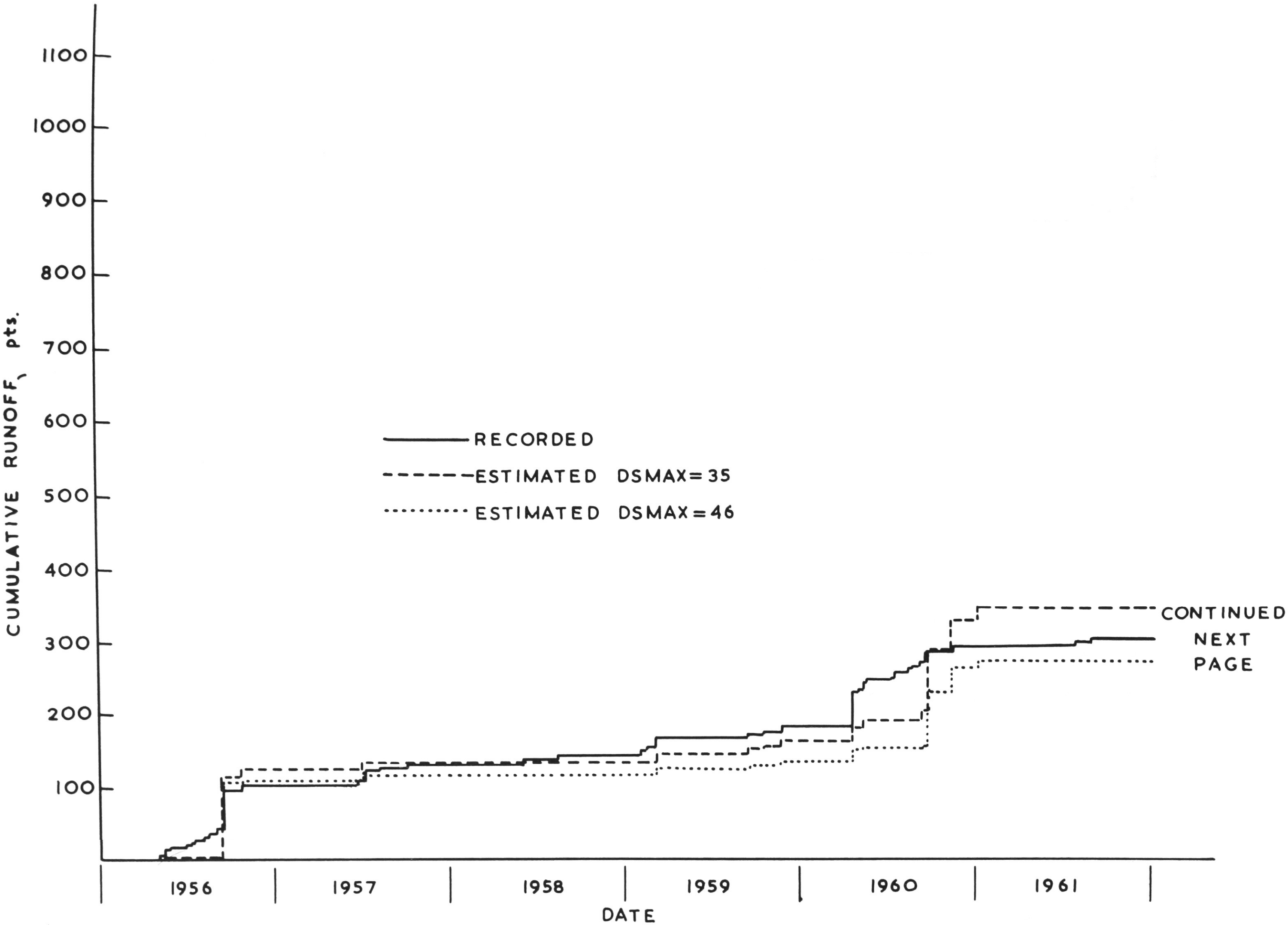


FIGURE 44: PARWAN WEIR - MASS CURVES FOR RECORDED AND ESTIMATED RUNOFF

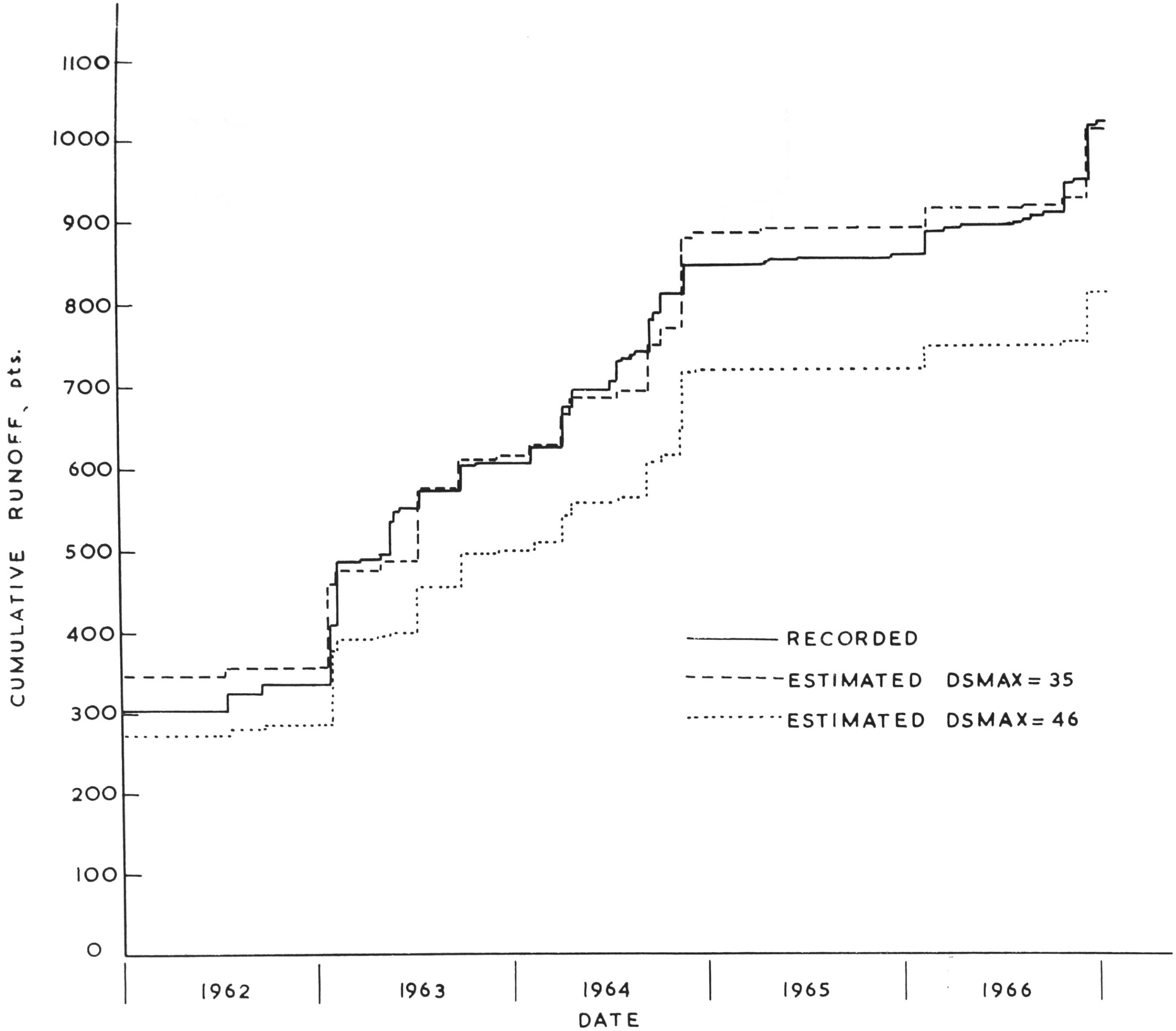


FIGURE 44 CONTINUED: PARWAN WEIR

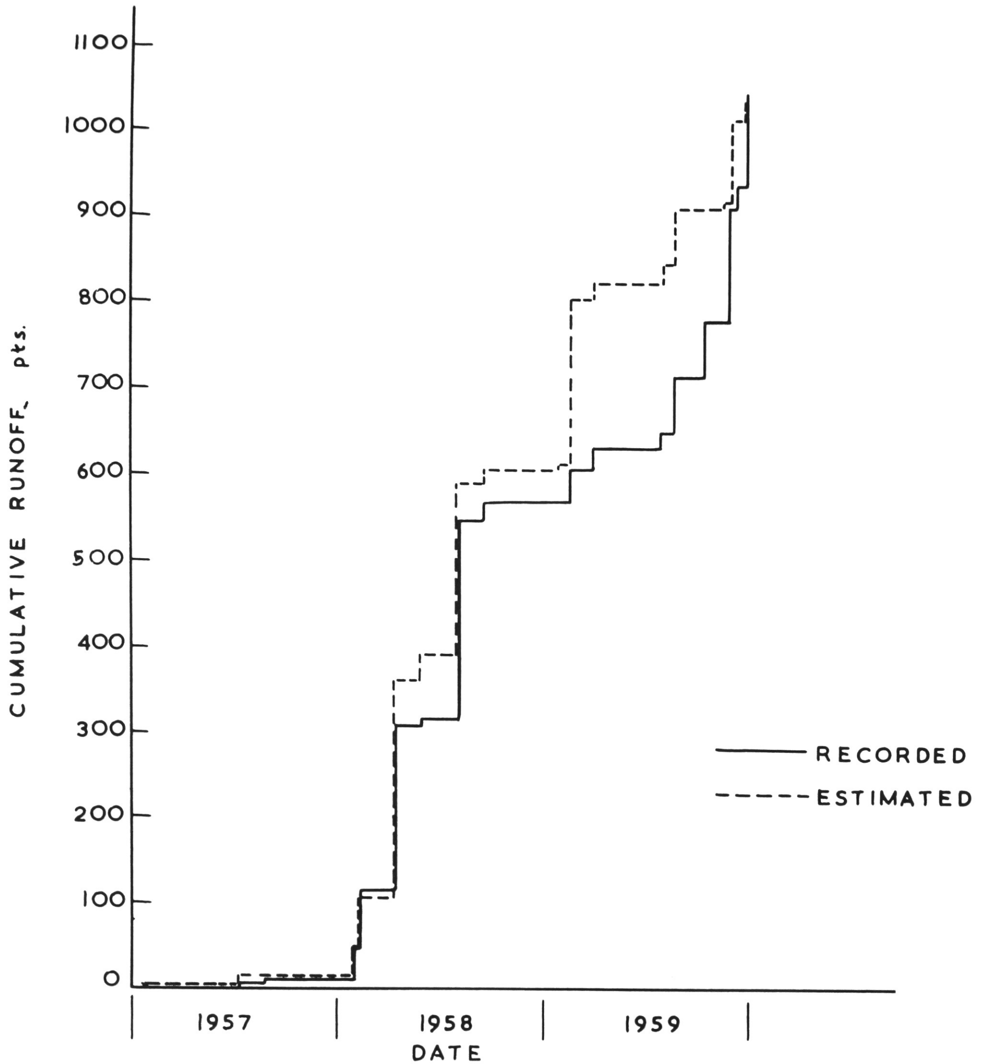


FIGURE 45: BADGERYS CREEK – MASS CURVES FOR RECORDED AND ESTIMATED RUNOFF

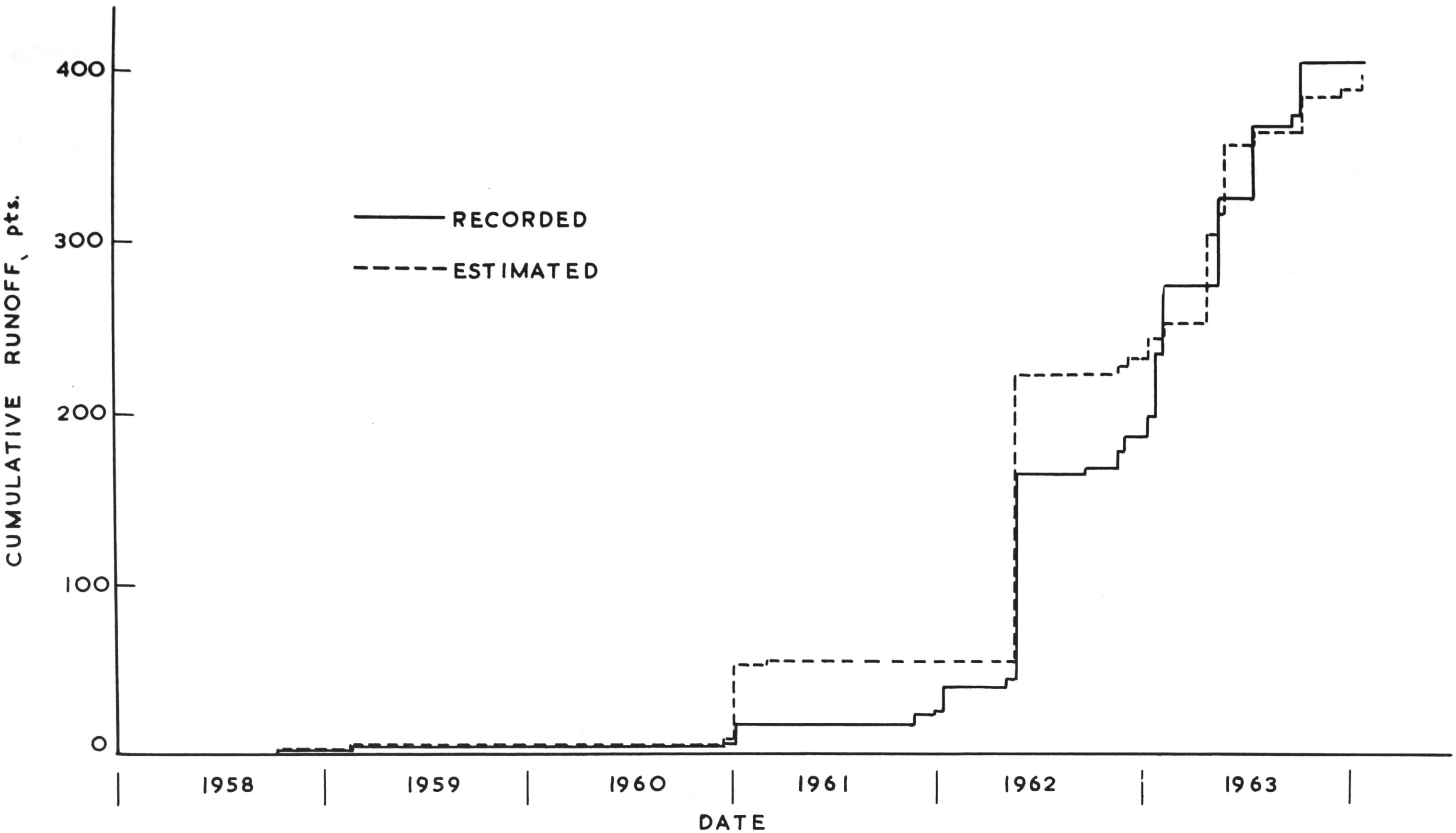


FIGURE 46: SCONE - MASS CURVES FOR RECORDED AND ESTIMATED RUNOFF

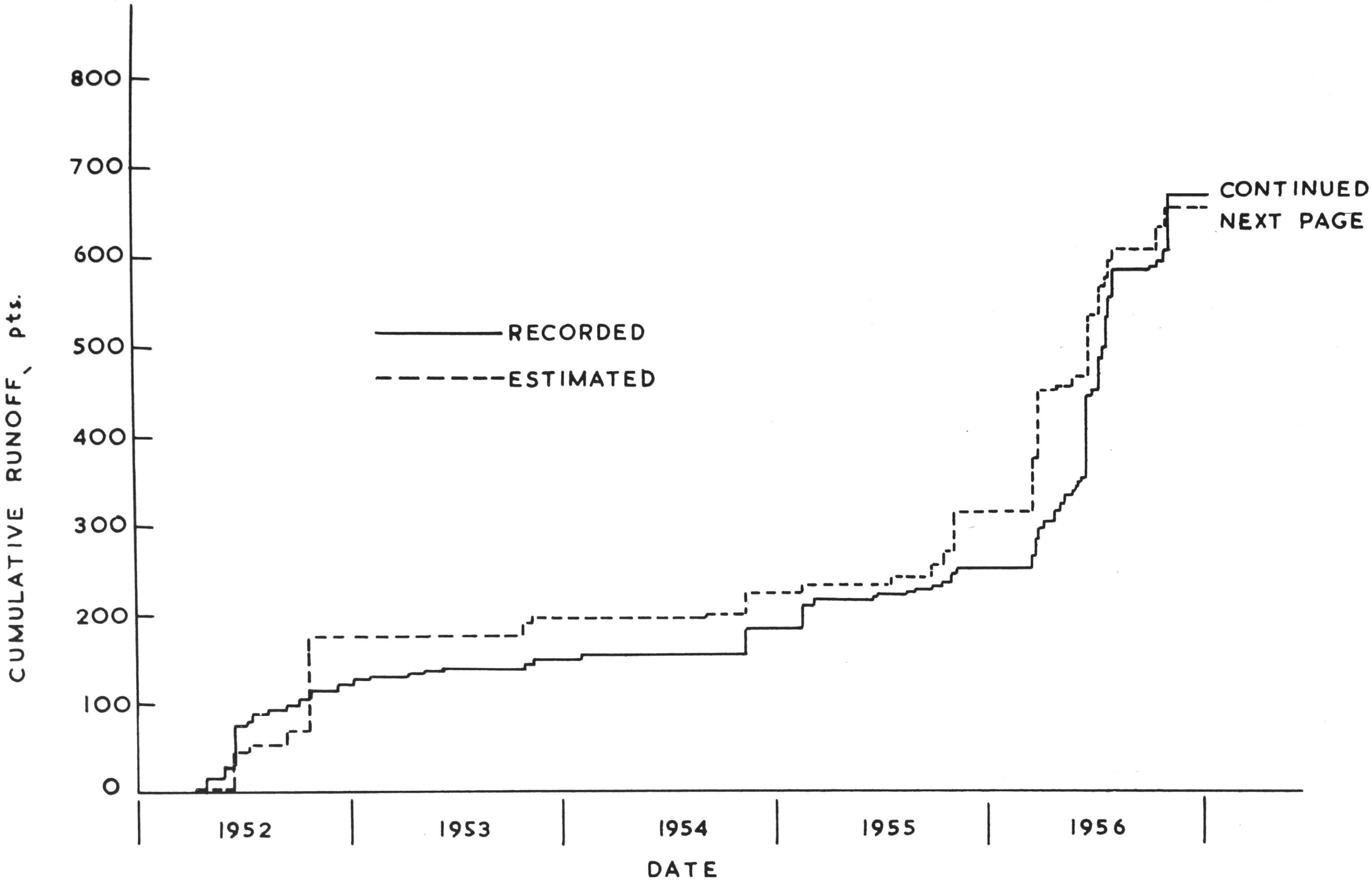


FIGURE 47: WAGGA WAGGA - MASS CURVES FOR RECORDED AND ESTIMATED RUNOFF

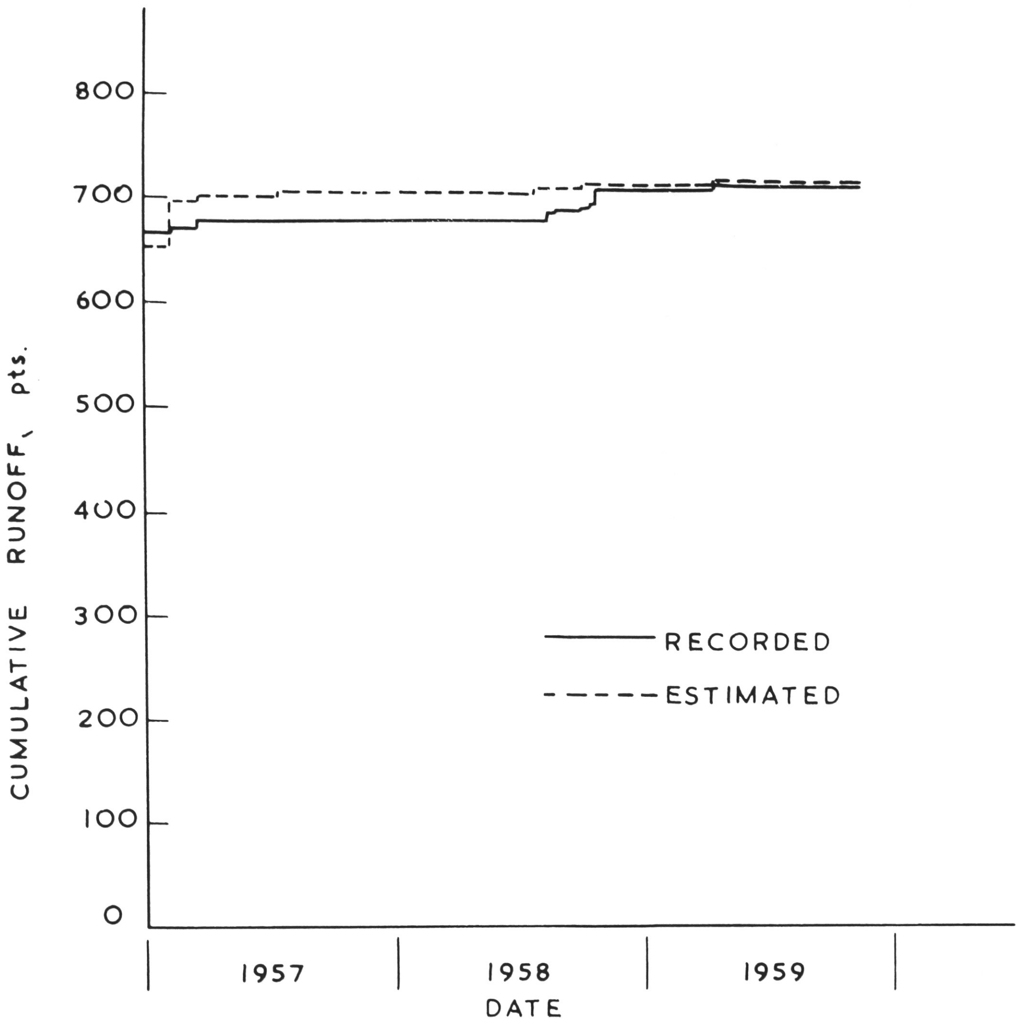
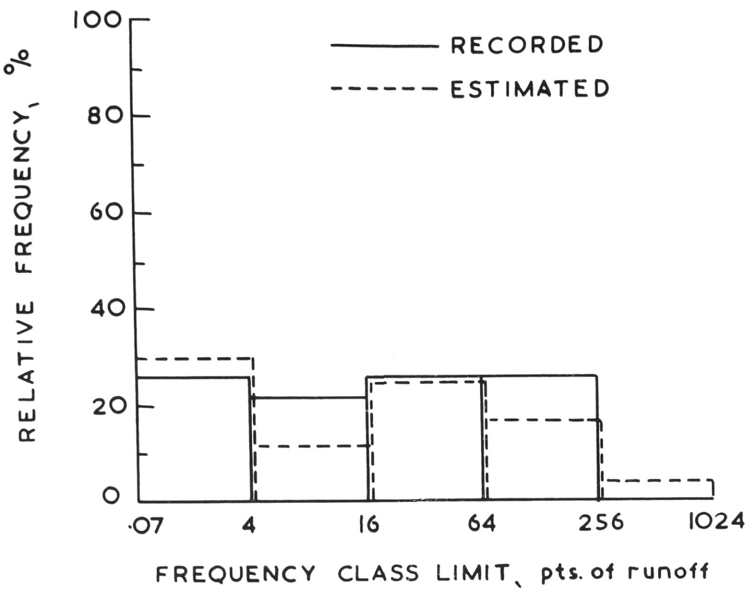
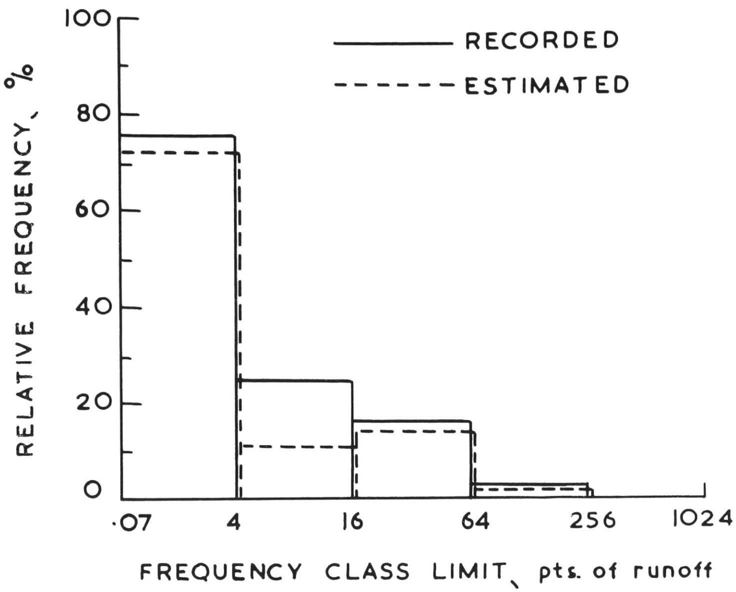


FIGURE 47 CONTINUED: WAGGA WAGGA



BADGERYS CREEK

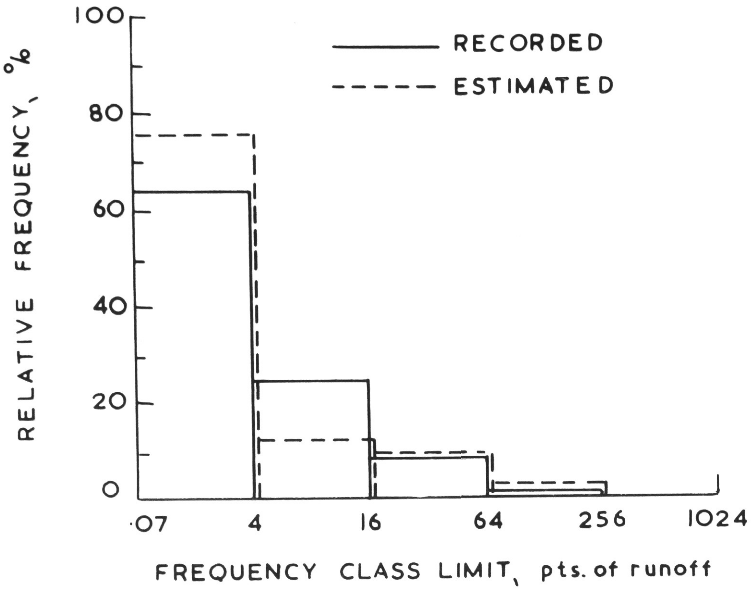
FIGURE 48



SCONE

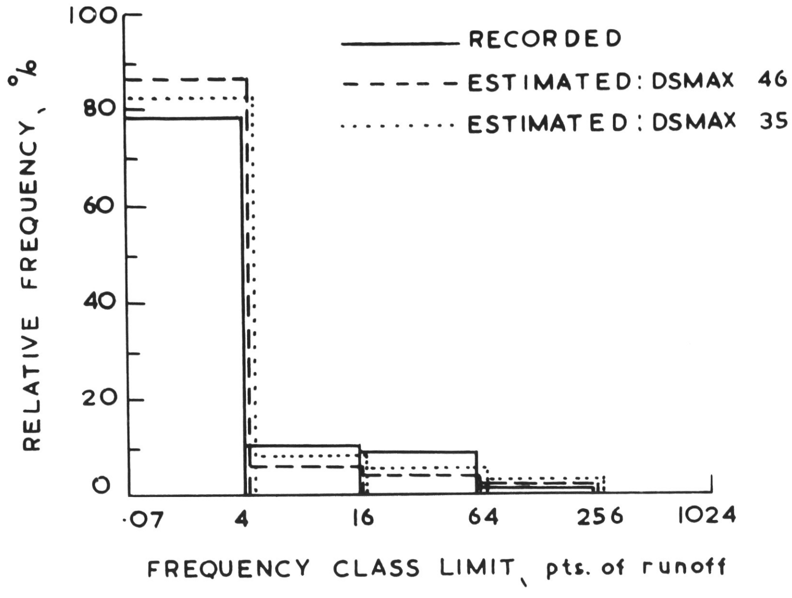
FIGURE 49

FIGURES 48 & 49: RELATIVE FREQUENCY OF RUNOFF



WAGGA WAGGA

FIGURE 50



PARWAN WEIR

FIGURE 51

FIGURES 50 & 51: RELATIVE FREQUENCY OF RUNOFF

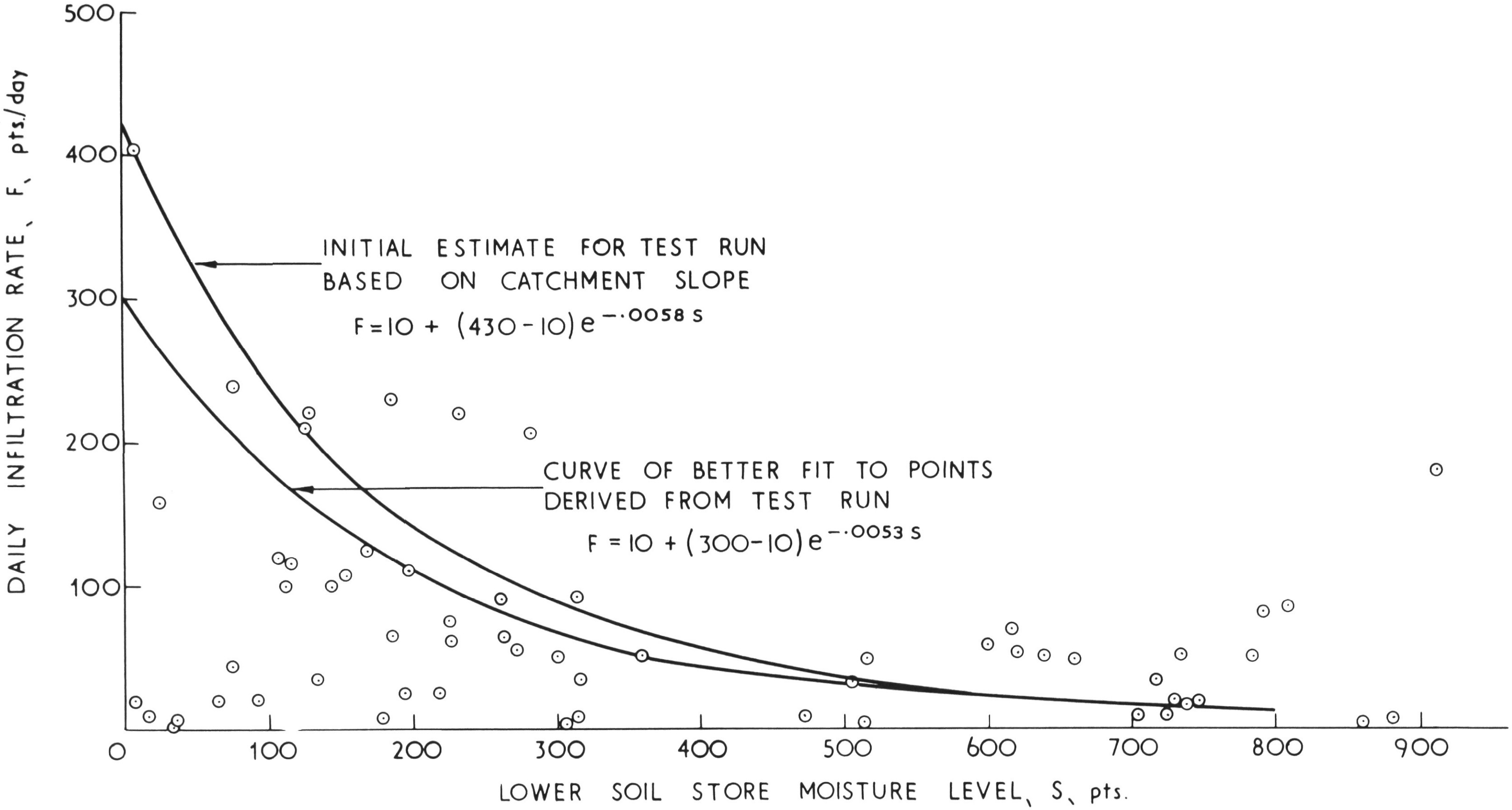


FIGURE 52: PARWAN WEIR - ESTIMATED INFILTRATION CURVES WITH DSMAX = 46 POINTS

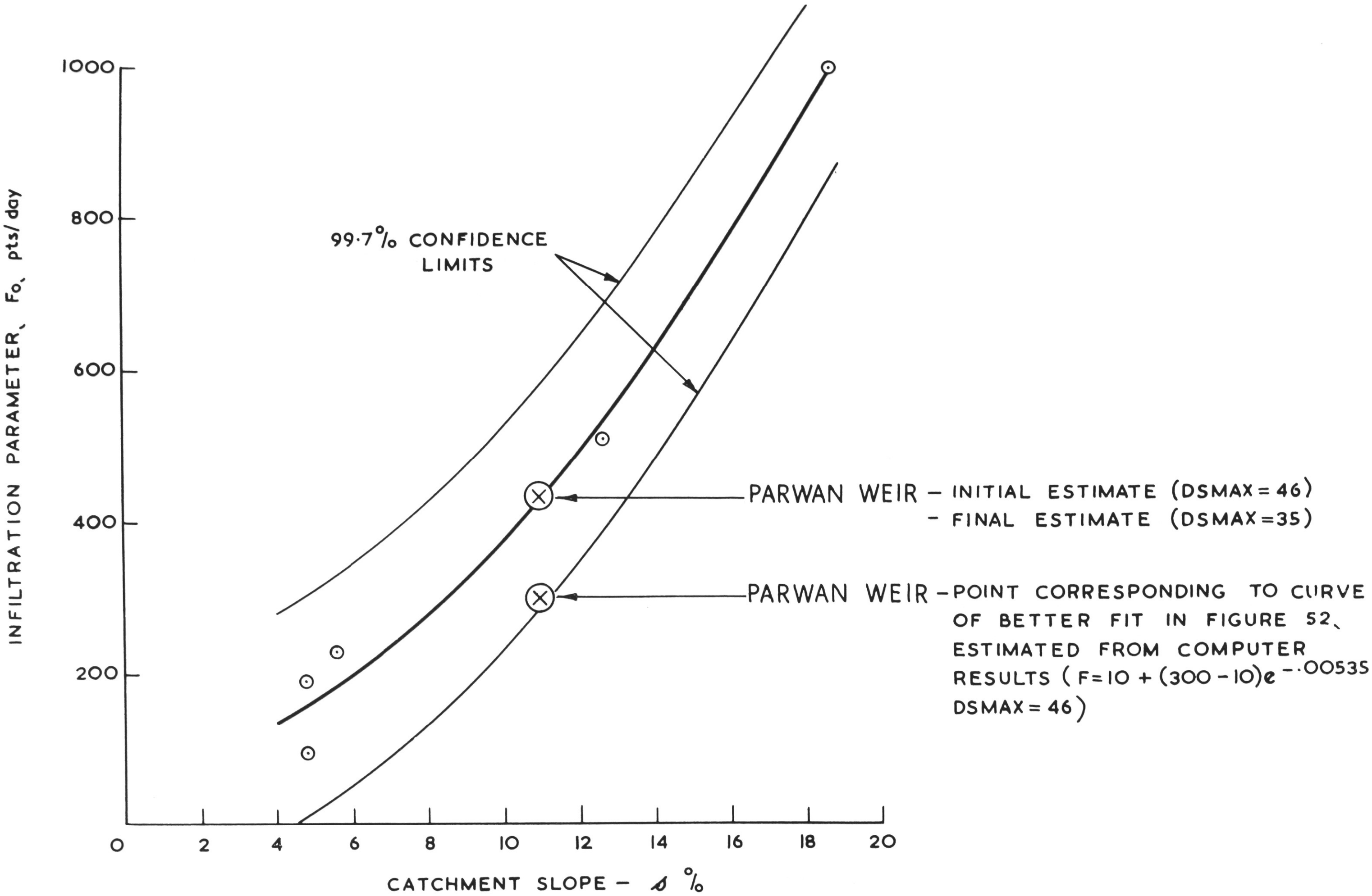


FIGURE 53: RELATIONSHIP BETWEEN F_0 & s, SHOWING INITIAL ESTIMATE & POINT FOR INFILTRATION CURVE OF BETTER FIT FOR PARWAN WEIR DATA, WITH DSMAX HELD CONSTANT AT 46 PTS.

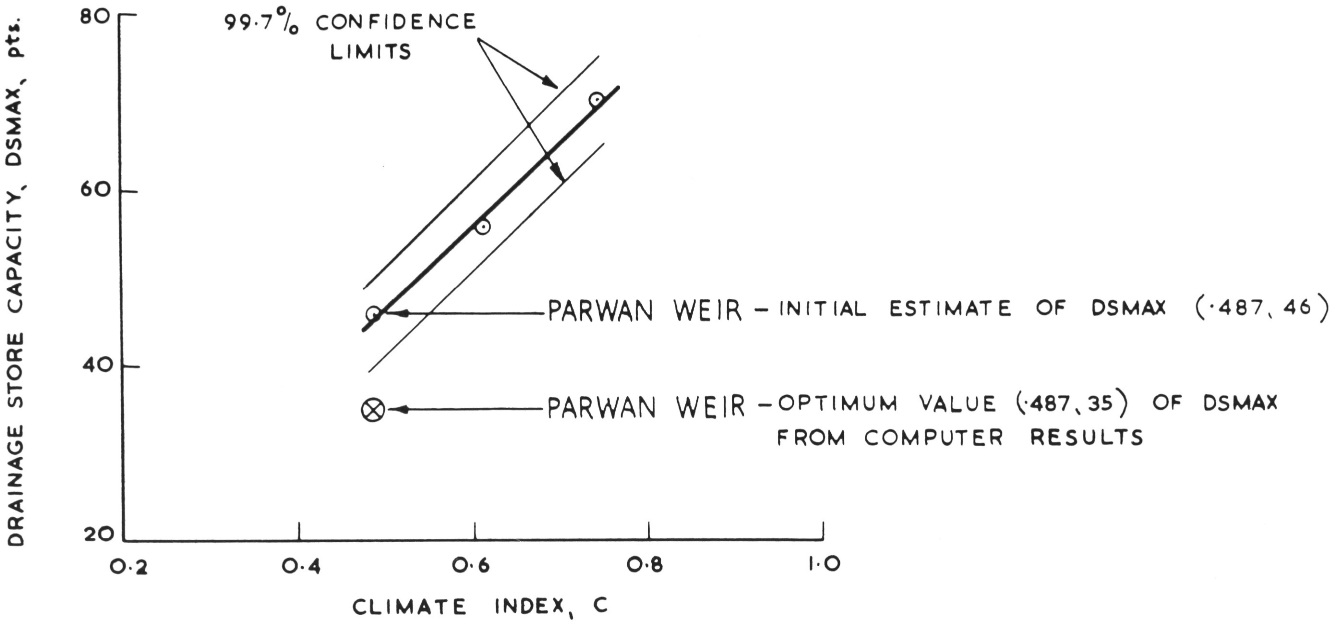


FIGURE 54: RELATIONSHIP BETWEEN DSMAX & C. EXAMINATION OF THE OPTIMUM VALUE OF DSMAX FOR PARWAN WEIR WITH RESPECT TO THE DSMAX VERSUS C CORRELATION