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Physical Data for Catchment Models

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The physical components of catchments that are commonly included in deterministic rainfall-runoff models are examined. Data are presented which can be used for design purposes, to provide a guide to the realism of parameter values that have been derived by optimisation procedures, or to facilitate the examination of overall model validity.

Introduction

This paper is concerned with the deterministic type of catchment runoff model, which operates on a digital computer and purports to simulate certain physical processes in the hydrologic cycle. Quite a number of these models have been proposed and attention is drawn to reviews by Bell (1966) and Laurenson and Jones (1968). Most of the models are similar in structure, with the variations being in particular sub-routines and the grouping of components, with each model having its strong and weak points.

There is a need to apply these models to ungauged catchments, which requires that the parameters be estimated from physical characteristics rather than from rainfall-runoff records. Derivation of the parameter values by optimisation techniques (e.g., steepest ascent, simplex) is not considered satisfactory, because the derived values may not be related to the true values which they claim to represent. Also, values derived by optimisation or iteration procedures can be misleading in that they balance out errors in other (false) parameter values and thereby lead to misinterpretation. There is also the likelihood that derived optimum values may be determined from rainfall-runoff records which do not cover all possible occurrences and these values can later cause difficulties.

Before commencing the work it was considered that information existed in the literature that could provide reasonable estimates of the catchment components used in most runoff process models. This information was known to be spread over several disciplines (agriculture, ecology, engineering) but it was considered that it could be collated and evaluated to obtain the required knowledge. It was also believed that as most models have been designed by subjective deduction, the collation of data could provide a means for checking on their validity.

The work reported herein was aimed at the grass roots level of catchments, to examine the basic physical components and determine what values of model variables are physically feasible.

Soil Moisture Properties

The major store components in catchment models are associated with soil moisture and the replenishment of these stores has a significant effect on the occurrence and volume of runoff. The actual soil properties which are involved can vary from model to model, depending on how the model has divided catchments into components and represented these in mathematical form, but basically the main parameters of most models are governed by the pore space characteristics and the associated soil moisture properties of the catchment soils.

Soil Pores and Soil Water

Soil pores may be classified by size to come within one of the following three groups:

Non-capillary
Capillary
Sub-capillary

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

Two classes of soil water may be associated with model parameters:

Gravitational water, located in the non-capillary pores
Available water, held in the capillary pores.

Three points of equilibrium define the limits of the soil moisture classes:

Saturation capacity
... Gravitational water
Field capacity
... Available water
Wilting point

The available and gravitational water capacities of a soil define the maximum quantity of each type of water that the soil can hold. If the thickness of the soil layer belonging to each soil moisture store is defined, then the capacities of the soil moisture stores can be calculated.

Available Water Capacity

Available water capacity (AWC) can be expressed as »mm of water/metre depth of soil«. The depth of soil in the upper and lower soil zones on a catchment multiplied by the corresponding AWC can give the capacities of the upper and lower soil moisture stores in a model. It is from these stores that most of the evapotranspiration on a catchment occurs.

AWC data covering the entire soil textural range has been presented by Shockley (1955) and this is listed in Table 1.

Table 1 - Available moisture capacity - Shockley, USDA (1955)

Soil description			Available moisture mm/metre	
			Range	*Average
Fine	> 40% clay	Clay, silty clay, sandy clay.	133-208	192
Mod.fine	27-40% clay	Silty clay loam, clay loam.	133-208	183
Medium	> 40% silt	Silty loams, silt loam.	133-208	192
Medium	0-39% silt	Sandy clay loam, loam, v. fine sandy loams, sandy loams containing less than 70% sand.	125-200	158
Mod.coarse	> 70% sand	Fine sandy loam and sandy loam containing more than 70% sand, & loamy fine sand	83-125	100
Coarse	<95% sand	Loamy sand, fine sand, coarse sand	67-83	75

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

Gravitational Water Capacity

Water in the non-capillary pores of a soil is regarded as having the property of being able to drain by the effect of gravity. This water is commonly termed gravitational water and the gravitational water capacity is equal to the non-capillary porosity

(NCP) of the soil. In studies of ground-water a synonymous concept is specific yield, which refers to the quantity of water that may be drained from aquifers.

Specific yield data will first be presented followed by NCP data for subsoils and then for surface soils.

Groundwater

Early measurements of specific yield were effected by Eckis and Gross (1934) and Piper et al (1939). Other groups have assessed this information and prepared further estimates. These include Davis et al (1959), Thomasson et al (1960) and Olmsted and Davis (1961). Taking this information into account, Table 2 has been prepared to indicate the general range of specific yield values.

More discrete data have been presented for particular valleys by various workers (e.g., Davis, Lofgren, and Seymour 1964, p. 26) but these may have bias to their locality of derivation.

Table 2 - Specific yield data

Material	Specific Yield %
Silts, very fine sands and clays	1-5
Fine sands and gravel in tight condition	10-20
Gravels, coarse to medium loose sands	20-35

Subsoils

Table 3 summarises NCP data generally from agricultural investigations and regarded as for material in a subsoil condition. The data were extracted from the work of Baver (1938), Kopecky (1927), Ayres and Scoates (1939) and Free et al (1940). For the medium to fine soils, subsoil NCP values would probably exceed the specific yield data in Table 2, due to the effects of soil structure. For surface soils, vegetation would increase the structure effect still further.

Free et al (1940) have presented subsoil data which permit a closer examination of NCP. Their data are based on total porosity minus moisture equivalent and represent measurements made on 68 catchments spread over the United States. An analysis of variance on these data showed that the variation in NCP between textures is statistically significant. The data were arranged into classes and the Chi-square test indicated a »very good« fit to a normal distribution with mean 14.4% and standard deviation 7.1%. These results may be compared with those obtained later for surface soils.

Table 3 - Subsoil NCP

Textural group: USDA classification	Description	NCP for group, %
Fine	Sandy clay, silty clay, clay.	6
Moderately fine	Clay loam, sandy loam, silty clay loam.	8
Medium	Very fine sandy loam, silt loam, silt.	11
Moderately coarse	Sandy loam, fine sandy loam.	16
Coarse	Sands: Coarse Medium Fine Loamy sands	24

Surface Soils

Surface soil NCP is a difficult property for which to establish design values, due to its variability, limited data and the problem of defining or measuring NCP. However, its evaluation is important because of the effect on initial loss and interflow.

The data of Dreibelbis and Post (1940, 1943) and Free et al (1940), were assembled and analysed statistically to ascertain the factors affecting surface soil NCP on catchments. The results were as follows:

(a) The following variations in surface soil NCP may occur;
 very significant variation between catchments in the same vicinity with similar soils but having different surface treatment,
 very significant variation between methods of measuring NCP,
 very significant variation in the NCP of a given surface soil at different times of the year.

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

(c) Soil structure is the factor most affecting surface soil NCP.

The NCP data (based on porosity minus adjusted moisture equivalent) and surface soil descriptions of Free et al (1940), Dreibelbis and Post (1940) and Shively and Weaver (1939, p. 24) were subjected to statistical analysis.

An analysis of variance indicated that the data of Free et al and Dreibelbis and Post could be regarded as from the same population. 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%. These results may be compared with those obtained previously for subsoils.

The NCP data and soil descriptions of Free et al and Shively and Weaver were sorted and information extracted to enable estimation of surface soil NCP for two particular conditions. From a sample of four catchments the mean and standard deviation of the NCP data for »crumb structure, dense grass« was calculated as 33.9 ± 1.8%. From a sample of seven other catchments the corresponding statistic for »range land, sparse to moderate grass« was 26.0 ± 3.6%. These statistics should provide reasonable estimates of NCP for the crumb structure and range land conditions.

Vegetation Root Habits

The depths and patterns of vegetation roots directly affect the evaporation behaviour of catchments. For a given type of vegetation, the root zone depth determines the depth from which moisture is removed by evapotranspiration. Some significant variables which affect the depth of roots are:

Plant type and age.
Soil characteristics such as texture, structure, compaction, aeration and fertility.
Level of the water table.
Climate and nature of the annual rainfall.

The 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:

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

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.

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.

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:

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 60 cm, scrub from 60-120 cm and large trees deeper still.

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.

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.

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.

Root Depths

Information regarding root depths was assembled from a number of sources, including Ozanne et al (1965), Laverton (1964), USDA (1951), Shively and Weaver (1939), Baver (1956, p. 445), Costin et al (1964), Meinzer (1942, p. 263), Russell (1958, p. 426), Donahue (1961), Aust. Standards Assn. (1967) and detailed measurements on Australian catchments by both the Author and the Soil Conservation Service of N.S.W. The important points evident from the collated information were:

(i) Most grasses have a concentration of roots (50% or more) in the top 15 cm of soil.
(ii) For a wide range of vegetation, 70-90% of the roots are included in the top 60 cm of soil.
(iii) The expected range for effective root depths of light natural vegetation is 8 to 90 cm.

Evaporation from Bare Soil

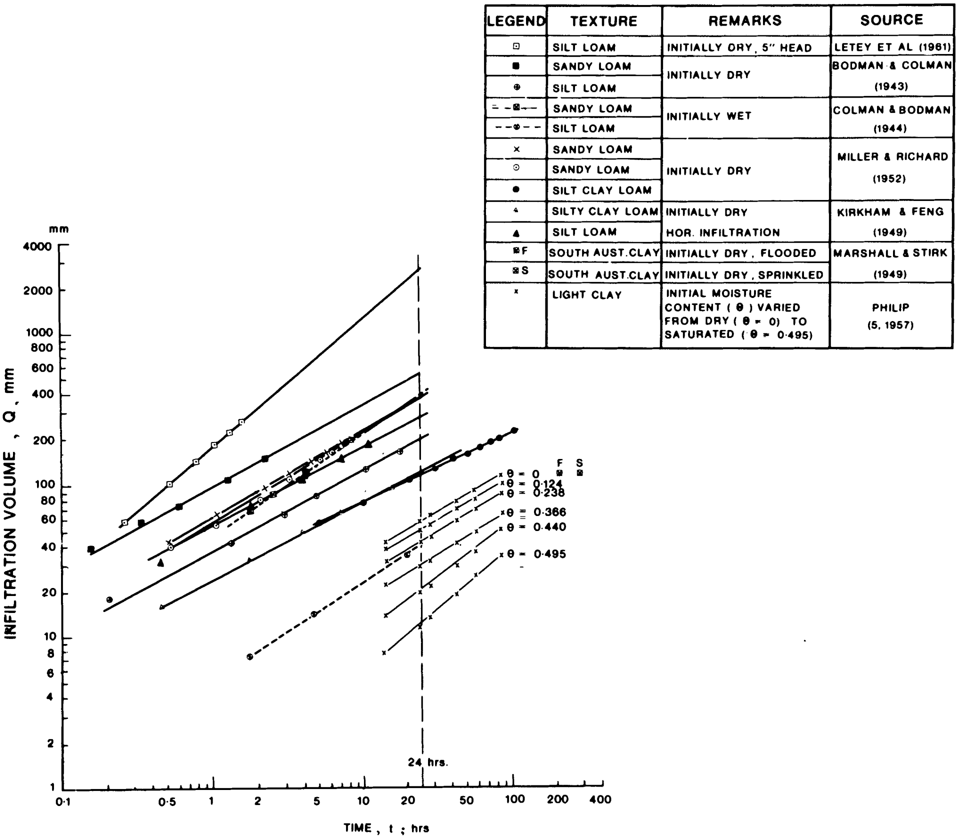
On a catchment with shallow rooted vegetation, direct evaporation could possibly remove moisture from a depth well below the roots. The literature on evaporation from bare soil was therefore surveyed to examine the feasibility of this hypothesis. The information obtained is summarised in Table 4 and 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 30 cm. Probably evaporation would occur from soil at a greater depth (30-100 cm), but at a very low rate. This excludes the situation where an extensive groundwater supply exists.

Table 4 - 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 15-20 cm there is little loss of moizure by soil evaporation.
Alway & McDole (1917)	At moisture contents near field capacity the movements of moisture upwards from below 30 cm is very slow.
Rotmistrov (Quoted by Meinzer 1942, p. 379)	Water which penetrates beyond 40-50 cm does not return to the soil surface except by way of plant roots.
McGee (1913)	Annually, 15 cm of water is brought to the surface by capillarity from depths as great as 300 cm from an extensive groundwater supply:
Richards & Neal (1936, 1937) Russell & Richards (1938, 1939)	Upwards movement of water by capillarity from depths to 60 cm.
Baver (1956, pp. 275-283)	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 90 cm and would probably be minor below about 20 cm.
Chow (1964, p. 6-18)	Surface evaporation can penetrate to a depth of 20-30 cm.
Meinzer (1942, p. 291)	Capillary rise may be 30 to 60 cm in sand, 120 cm in sandy loam and up to 300 cm in clays. For heavy soils including clay loams and adobes (calcarous sandy clays), soil evaporation practically ceases when the water table reaches a depth of 120 cm, even though the capillary limit may exceed this figure.

Infiltration

In catchment models, infiltration is problably the most elusive physical process for which to establish design data, due mainly to limited knowledge on the behaviour of moisture after it passes into catchment soil. Here, two sources of information will be examined to ascertain the general order of values which can reasonably be assigned to infiltration parameters. The two sources are experimental infiltration data and storm loss rate data.



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	COLMAN & BODMAN (1944)
- -⊕- -	SILT LOAM		
×	SANDY LOAM	INITIALLY DRY	MILLER & RICHARD (1952)
⊙	SANDY LOAM		
●	SILT CLAY LOAM		
▵	SILTY CLAY LOAM	INITIALLY DRY	KIRKHAM & FENG (1949)
▲	SILT LOAM	HOR. INFILTRATION	
▨F	SOUTH AUST.CLAY	INITIALLY DRY, FLOODED	MARSHALL & STIRK (1949)
▨S	SOUTH AUST.CLAY	INITIALLY DRY, SPRINKLED	
×	LIGHT CLAY	INITIAL MOISTURE CONTENT (θ) VARIED FROM DRY (θ = 0) TO SATURATED (θ = 0·495)	PHILIP (5, 1957)

Fig. 1. Infiltration volume versus time relationships for soils of various textures

Infiltration Data

A limited amount of infiltration data have been reported in the literature, these having been derived either analytically or by experiment. Some of the data provide direct physical values while others have been further processed using infiltration and soil moisture theory. The assembled data are shown in Fig. 1.

The representative values in Table 5 were estimated using the data illustrated in Fig. 1. Both the 24 hour and 1 hour volumes of infiltration vary fairly uniformly with soil texture, decreasing from sandy loam to light clay. The decrease in infiltration with increasing initial moisture content may also be noted.

Table 5 - Variation of infiltration with soil texture and moisture content

Texture	Initial moisture condition	1 hr. volume of infiltration mm	24 hr. volume of infiltration mm
Sandy loam	dry	97	530
	field capacity	47	380
Light clay	dry	9	56
	wilting point	7	45
	field capacity	2	22
	saturated	1	12

Loss Rate Data

A derived loss rate includes all water retained in the soil during a storm (excluding initial loss), depression storage and evaporation during the storm. Hence the loss rate may include some components which are represented separately in computer type models.

Laurenson and Pilgrim (1963) have presented 150 loss rates for 24 Australian catchments and Pilgrim (1966) has shown that these rates could be assumed as from the same population as a collection of 460 loss rates from 101 catchments in the United States and 106 rates from 8 catchments in New Zealand.

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

$$API \equiv AP_1 + 0.69(AP_7 - AP_1) + 0.16(AP_{28} - AP_7)$$

where AP_n = n days antecedent rainfall.

The equation was adapted from an expression proposed by Cordery (1970), $API_i = P_i + K\,(API_{i-1})$, with K having a value near 0.9 and P_i being the rainfall on the ith day. For K, median regression values of 0.69 and 0.16 in the series 0.9^{n-1} were used for 2-7 and 8-28 previous days respectively. The loss rates were arranged into a relative frequency histogram as shown in Fig. 2. The median API is 1.37. 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.

A sample of seven loss rates was obtained for »summer dry« with a median of 5.1 mm/hr, and this rate was derived using a time period of 2 hours. During the 2 hour period the total loss was therefore 10.2 mm.

For »winter wet« the sample comprised eleven loss rates, with a median of 1.5 mm/hr, derived using a time period of 1 hour.

These values were extended to 24 hour rates using the relationship $Q = ct^b$ (Kostiakov 1932). The exponent b may range from 0.5 (soil very dry) to 1.0 (soil saturated).

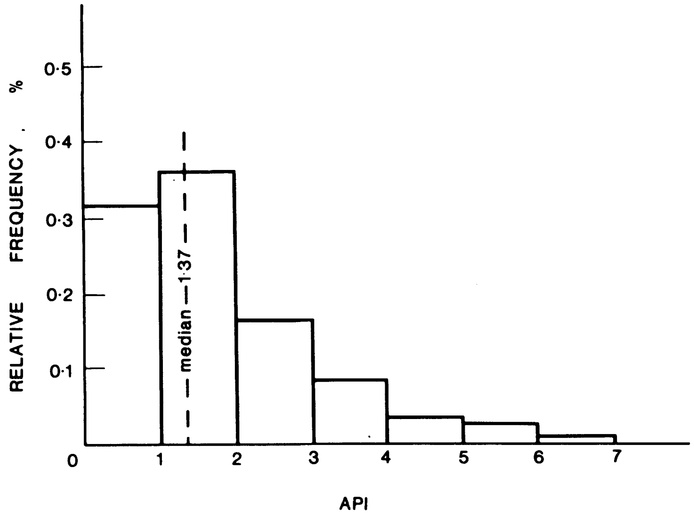


Fig. 2. *API* relative frequency histogram.

For a moisture condition of wilting point (catchment dry) a value of 0.6 was adopted. For field capacity (catchment wet) a value of 0.75 was selected, as suggested by Krimgold Beenhouwer (1954).

The equation $Q = ct^b$ can be drawn if the slope (b) and one point on the line are known. In Fig. 3 a line of slope 0.6 passing through the point representing the median »summer dry« loss rate (2 hr, 10.2 mm) indicates a 24 hour volume of 45.7 mm and a 1 hour volume of 6.7 mm. Similarly, a line of slope 0.75 passing through the point representing the median »winter wet« loss rate (1 hr, 1.5 mm), indicates a 24 hour volume of 16.5 mm.

In Table 6, the 1 hour and 24 hour values derived from loss rates for conditions of »winter wet« and »summer dry« are compared with equivalent infiltration data from Table 5. It may be noted that the agreement is quite close for all four pairs of comparisons. This indicates that the loss rate values losses into clay subsoil and may be used for that component in catchment models.

Table 6 - Infiltration and loss rate data comparison

Condition		mm per hour		mm per 24 hours	
		Infil-tration	Loss rate	Infil-tration	Loss rate
Wilting point	OR Summer dry	7.0	6.7	45.0	45.7
Av. of field capac. & saturated	OR Winter wet	1.5	1.5	17.0	16.5

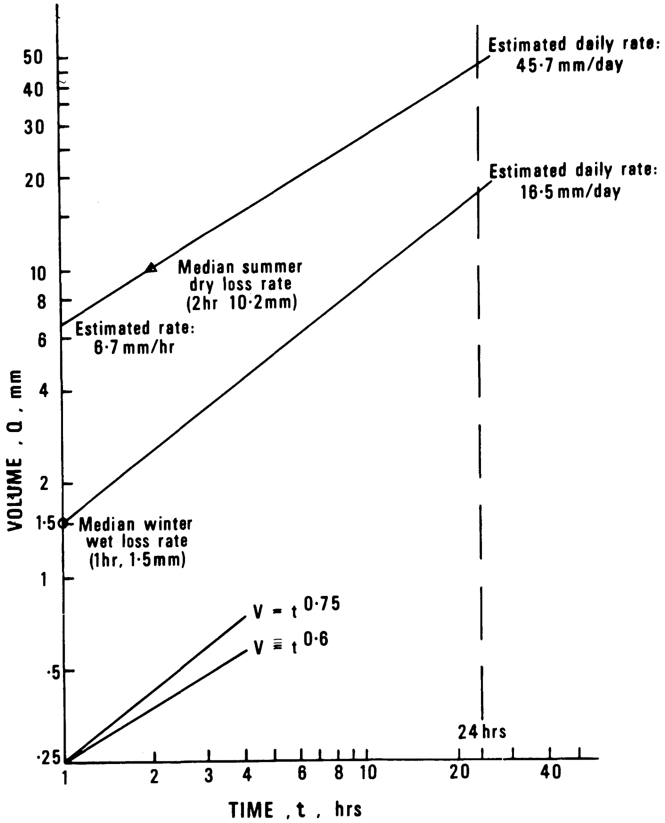


Fig. 3. Estimation of daily volume of infiltration from median loss rate.

Interception Storage

Interception loss *(I)*, comprises water stored on the surface of vegetation (vegetation storage, *V)* plus water which evaporates from the vegetation surface during the storm *(at)*. This equation, $I = V + at$, is illustrated in Fig. 4.

Other equations have also been fitted to interception data and attention is drawn to Zinke (1967), Leyton et al (1967), Helvey and Patric (1965) and Johnson (1942). For example, the equation $P_n = bP - V$ has often been used, with Pn and P being net and n gross rainfall and V again being interception storage.

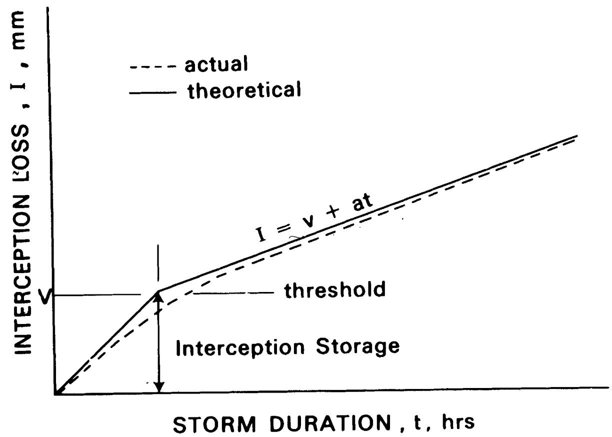


Fig. 4. The components of interception loss.

Values of *(V)* were extracted from the literature and collated as shown in Table 7, in the following groups:

(i) Field data, fitted by regression equations.
(ii) Theoretical calculations based on wetted surface area and water film thickness.
(iii) Laboratory measurements of sprinkled vegetation.

Analysis of variance on the data, normalised by logarithmic transformation, indicated there to be no significant variation due to the method of derivation (field, theoretical, laboratory) but that the type of vegetative cover may have a significant effect. However, further analysis indicated that this latter finding was probably an anomaly due to the small number of data items in some of the cover groups.

The data are presented as a histogram in Fig. 5. The median is 1.09 mm with 76% of the data in the range 0.19-1.50 mm and 93% in the range 0.19-2.00 mm.

The literature indicates that to achieve further refinement, it would be necessary to base estimates on more detailed information, including leaf surface texture and the ratio of exposed leaf area to projected ground area (Horton 1919; Clark 1940; Merriam 1961; Leyton et al. 1967). At present, adequate data for this are not available. For practical purposes, it would be appropriate to adopt a value of 1.1 mm for all types of single layer tree, crop or grass cover.

The above data do not include snowfall interception, for which only limited information is available and the spread is quite large. The snowfall data of Rowe and Hendrix (1951), Kittredge (1953) and Morey in Johnson (1942) have a median of about 2.5 mm. However, this would be a less reliable value than that presented above for rainfall interception.

Table 7 = Estimated values of V (pts) for tree, grass and crop cover

Derivation of Data	Vegetative Cover					
		* Grass				
	Trees	H1	H2	H3	Crops	Shrubs
Field:						
Horton 1919	0.89	0.25	0.51	1.02	0.81	
Johnson 1942	0.76					
Rowe 1941	0.51					
Niederhof & Wilm 1943	0.74					
Rowe & Hendrix 1951	3.05					
Wood 1937	1.65					
Helveg & Patric 1965	0.58					
Leyton et al 1967	1.17					
Clark 1940			0.51			
Rutter 1963	1.60					
Law 1957	2.50					
Theoretical:						
Horton 1919	1.42				1.19	
Steiger 1920 - Penman 1963			0.41	0.91		
Flory - Penman 1963		1.07			0.51	
Clark 1940 - Penman 1963	1.37			1.91		
Voigt & Zwolinski 1964	0.64					
Laboratory:						
Clark 1940		0.76	1.75			
Grah & Wilson 1944						1.09
Leyton et al 1967		0.19				1.63
Burgy & Pomeroy 1958		1.14				
Merriam 1961		1.14				
Beard 1956		1.78	1.02	2.79		
Rutter 1963	1.35					
Not ascertained:						
Hicks 1943 - Zinke 1967						1.15
Hamilton & Rowe 1949, - Zinke 1967	1.30					1.75
Blaney et al 1930 - Zinke 1967	1.02					
Paul & Burgy 1961 - Zinke 1967	0.80					
Brookes 1950 - Leyton et al 1967						1.27

* Grass H1: mat-600 mm, H2: 600-1800 mm,
H3: 1800 mm plus

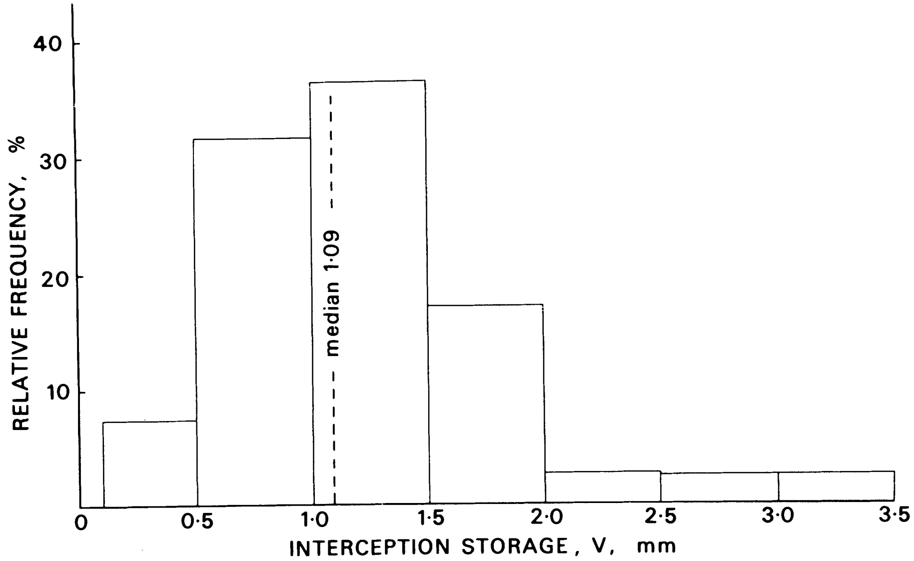


Fig. 5. Histogram of *V* data.

Conclusions

It was intended that the work reported in this paper would have two applications. Firstly, to enable reasonable estimates of model parameters from physical characteristics for ungauged catchments. Secondly, to enable model parameter values which have been estimated from theory or calculated by iteration procedures, to be examined for physical feasibility.

It is considered that the information now reported approaches the original aims and, more specifically, enables estimation of the following catchment characteristics which are usually included in the components of deterministic rainfall-runoff models:

The soil moisture storage characteristics of defined layers of soil (AWC, section on Soil Moisture Properties).

The initial loss capacity of defined layers of soils (NCP, section on Soil Moisture Properties).

The depth to which significant evaporation will occur, or the total thickness of the soil moisture storage layers which contribute to evaporation (section on Vegetation Root Habits).

The infiltration capacity of certain soils (section on Infiltration).

The interception storage capacity of vegetation (section on Interception Storage).

The work has indicated two main areas where most models have departed significantly from the true behaviour of catchments. Firstly, the pore-space characteristics of a surface soil change markedly throughout each year and between years, depending on the season and rainfall and their effects on vegetation. This alters the NCP of the surface soil, changing its interflow and initial loss characteristics and affecting all runoff events. Runoff calculations from small quantities of rainfall are particularly affected, because the »average« initial loss value which is commonly adopted for a model, may be nowhere near the true value at a particular time.

Secondly, infiltration has been a very difficult physical process to represent satisfactorily and to establish convincing design data for, in models. This is due largely to a lack of knowledge on the behaviour of water after it passes into soil on catchments. The situation has been complicated by a rather loose assignment of the term »infiltation« to model functions. This can result in infiltation becoming a parameter for adjusting calculation errors in other model functions, including changes in soil moisture storage, evaporation, redistribution below the evaporation zone and catchment leakage. This type of anomaly arises particularly when model functions or parameter values are derived by optimisation procedures. At present, it is considered that the best method of overcoming this problem would be the precision monitoring of water movements into, within and out of catchments. The measurement of moisture movements within the soil layers over catchments is considered to be of the most importance.

Acknowledgment

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