NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE of HYDROLOGY

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A CONCEPTUAL RUNOFF MODEL FOR THE CAM CATCHMENT

by

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ABSTRACT

The hydrological response of the 200 km^2 catchment of the River Cam above Dernford Mill, Cambridgeshire, is shown to be considerably more uniform than would be expected for an area half covered by boulder clay and half exposed chalk. Percolation to the groundwater system is found to take place over practically the whole area. As a consequence, a 'lumped' conceptual model was thought adequate to simulate the catchment response to precipitation. The resulting model simulates the groundwater system and its contribution to streamflow adequately, although the modelling of surface runoff events proves more difficult, due to the artificial controls present in the catchment.

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1. INTRODUCTION

1.1 Purposes and objectives

The simulation of runoff processes of a catchment is an important aid in forecasting river flows and for managing the water resources of river basins. Ideally, the parameters of such a simulation model should be determined objectively and should be closely related to measurable or predictable physical basin characteristics. Differences in parameter values may then be examined in light of physical changes on a basin, natural or man-made, or changes in basin characteristics from one catchment to another.

The Cam catchment, drained by the River Cam above Dernford Mill, has been selected for the purpose of developing a runoff simulation model for a permeable basin. The objectives of the study have been (i) to hypothesize a conceptual runoff model for the Cam catchment, and (ii) to test the suitability of the model for selected periods of measured input data.

1.2 The physiographic setting

Located approximately ten miles south of Cambridge, the Cam catchment comprises 197 km^2 of predominantly agricultural countryside. The basin is situated on the margin of the Fens; in the headwaters and further to the southeast lie the till covered Chalk uplands and to the northwest lies the western plateau. The central branch of the river rises in the Chalk uplands south of Saffron Walden, and flows slightly west of north to the gauging station near Dernford Mill. A map of the catchment and its location are shown in Figure 1.

The Chalk uplands are characterized by a low Chalk plateau with a variable, and often considerable, thickness of Boulder Clay as a superficial deposit (Sparks, 1957). The plateau is bounded to the northwest by a gentle and irregular escarpment. The Boulder Clay, deposited to maximum depths on the eastern and western topographic divides of the catchment, stretches almost to the present valley bottom at a number of locations. The general topography (Figure 1) in conjunction with the distribution of Boulder Clay (Figure 2) suggests that the valleys are largely pre-Boulder Clay features, as is the escarpment.

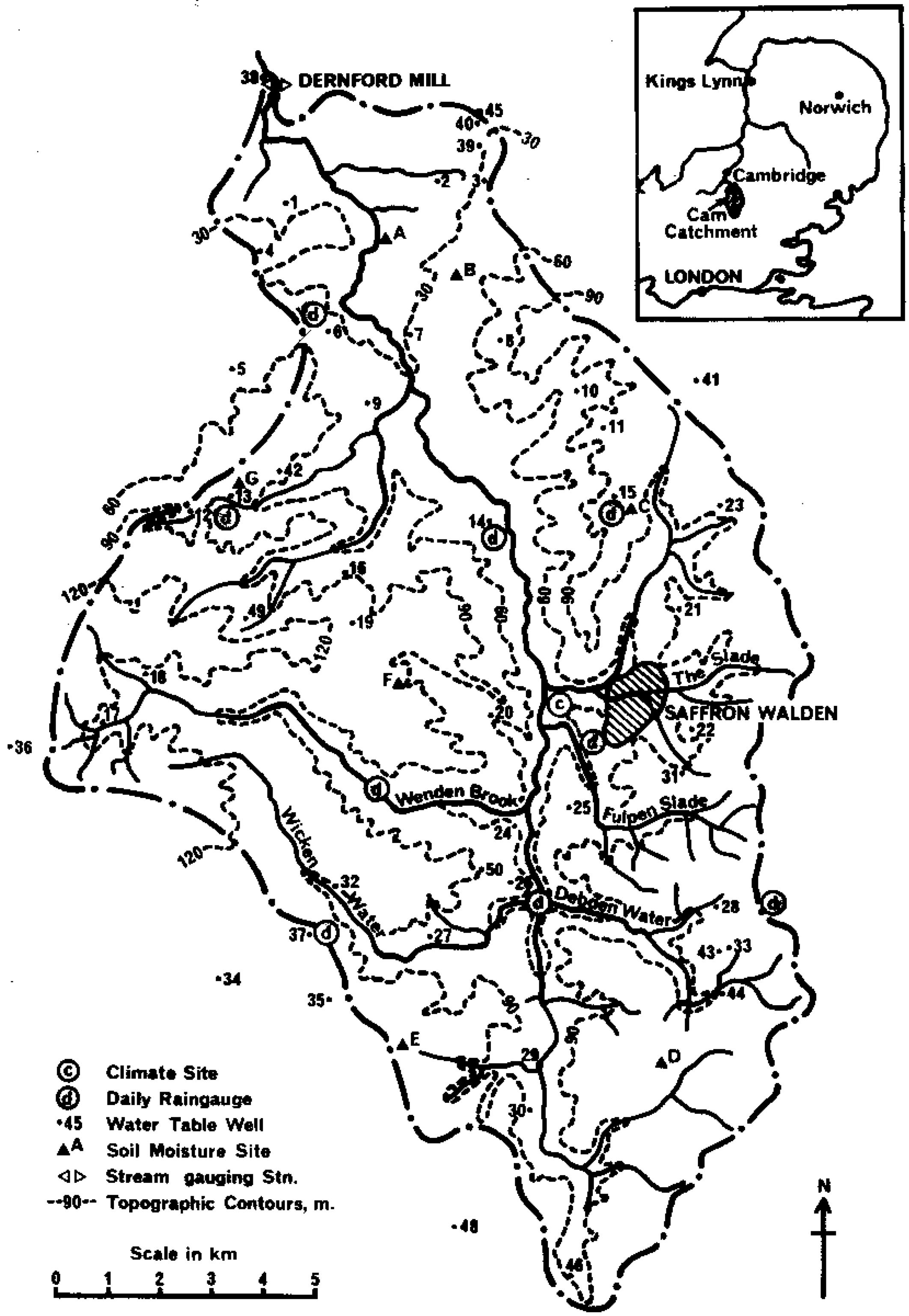


FIGURE 1 THE CAM CATCHMENT ABOVE DERNFORD MILL

The Chalk formation rests on the Cambridge Greensand, a concentrate of coarse material derived from clay (Steers, 1965). The Greensand and the underlying Gault Clay exhibit a low regional dip to the southeast, causing outcrops in the Chalk to form belts tending northeast to southwest. Of particular interest is a hard, relatively impermeable band of Greensand which outcrops in the vicinity of Dernford Mill. The presence of this band is likely to prevent the occurrence of much subsurface seepage northwards past the river gauging station.

In the mass, the Chalk is very porous, holding water in about one third of its total volume when saturated (Woodland, 1946). However, the pores are small and water is held largely by capillary action. As a result, the water carrying capacity of the Chalk depends on the existence and character of fissures. The effective porosity, thought to be about 1.5 to 2.0 percent (Hunter Blair, 1965; Steers, 1965), is likely to be dependent therefore upon the distribution and size of the fissures. The Chalk is so porous and well fissured that virtually all water falling upon it percolates, resulting in little, if any, direct runoff. Only in the valley bottoms, where the formation may be saturated to the surface, does surface runoff occur.

On the other hand, the Boulder Clay deposit is thought to be considerably less permeable (Woodland, 1946; Thomasson, 1969). Typically, it yields little water; however, it may become very pebbly in places, or contain patches of rubbly chalk or layers of sand and gravel, leading to the presence of small if unreliable water supplies.

Whereas direct measurements of percolation have been conducted in the Chalk (Woodland, 1946), yielding annual amounts of 150 to 180 mm, no measured values are available for the Boulder Clay. Woodland (1946) and Hunter Blair (1965) assumed a percolation rate for the deposit of 50 mms per year. From the fissured nature of the Chalk and the variable composition of the Boulder Clay, it seems likely that percolation rates for both may vary considerably over the catchment. Such variability is noted in the surface drainage characteristics given in Figure 2.

The presence of a buried channel beneath the central branch of the river has been reported and documented (Woodland, 1946; Steers, 1965). Starting at Whittlesford, the channel deepens southward, departing from the present course of the Cam near Quendon. It is deep, narrow, steep-sided and filled to depths of 60 m with a chalky silty till. Due to the nature of this fill material, and to the observation that buried channels in the region are not graded to a base level but rather undulate unevenly in a series of rock basins, it appears unlikely that much underground seepage occurs out of the catchment by way of the buried channel.

The precipitation pattern over the area is fairly uniform, with an average rainfall of about 635 mms. Woodland (1946) has noted the seasonal distribution for the period 1877 to 1944, with a low in March of 41.5 mms, and the wettest months of July and October yielding 68.8 mms and 65.6 mms respectively.

The annual potential transpiration for Cambridgeshire is approximately 530 mms (Ministry of Agriculture, Fisheries and Food, 1967). The seasonal pattern is very marked, with 460 mms during the summer period from April to September, and 70 mms in the winter months.

1.3 Data networks

The network of hydrological instruments located in and around the Cam catchment during the interval 1966 to 1970 is shown in Figure 1. The data collected from the various field instruments have been checked and utilized for the computation of (i) river discharge, (ii) mean basin precipitation, (iii) potential evaporation and transpiration, and (iv) mean basin soil moisture status.

The river discharge has been determined for two hourly intervals from the continuous river stage record and a stage : discharge relationship developed by the Great Ouse River Authority. Daily mean basin precipitation has been computed as the Thiessen average of the gauge network. Hourly precipitation was obtained by distributing the basin mean in time according to the continuous gauge record obtained at the climate station. Potential daily evaporation and transpiration estimates have been determined from the equations presented by Penman (1948). From each set of soil moisture data, a mean basin soil moisture condition has been determined. The above data are stored on magnetic tapes

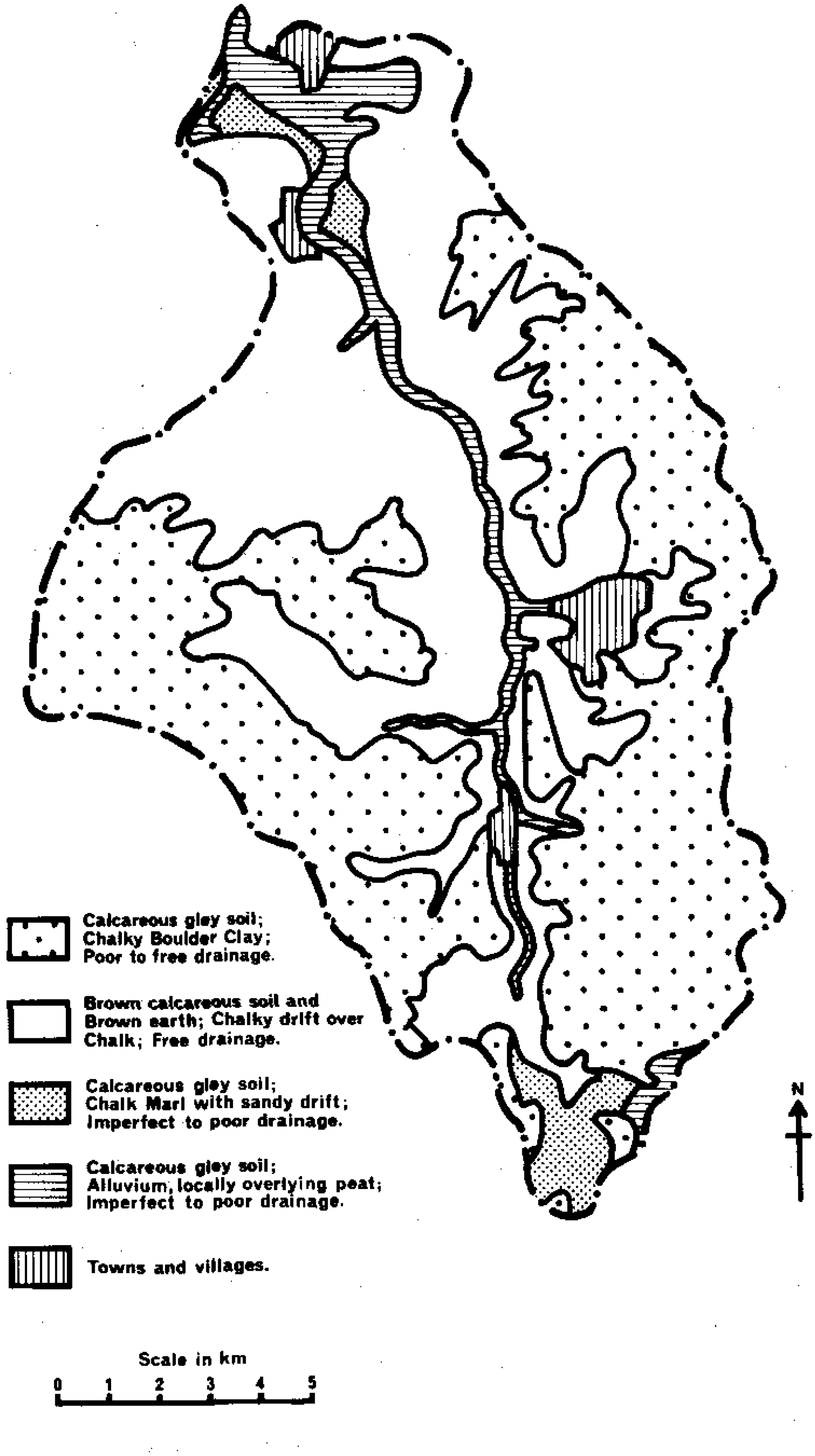


FIGURE 2 SOILS AND SURFACE DRAINAGE CONDITIONS ON THE CAM CATCHMENT (after Thomasson, 1969)

and are readily available for computer analysis.

2. HYDROLOGICAL PROCESSES

Examination of the setting of the Cam catchment reveals two aspects of the hydrological flow regime which warrant some investigation prior to the development of a simulation model. Firstly, the role which the Boulder Clay plays in determining direct runoff and recharge to the groundwater system requires some clarification. Secondly, it would be helpful if the storage characteristics of the Chalk and their areal variability within the catchment were better understood. The data available for the experimental catchment has allowed study of these aspects.

2.1 General volumetric response

Preliminary analysis of the runoff hydrographs for the period January 1966 to December 1970 reveals that an average of only 30 percent of the water falling as precipitation discharges into the river during a year. Further, 80 percent of this runoff occurs as baseflow, or as slow response. Data collected between 1952 and 1962 (Hunter Blair, 1965) also show that only 25 to 30 percent of the rainfall runs off above Dernford Mill. Such figures are indicative of an extremely permeable catchment.

Monthly runoff percentages pertaining to rapid or direct runoff volumes also denote high permeability. Values determined by dividing the estimated direct runoff by the precipitation during each monthly interval range between 0.4 and 19.0 percent for the period 1966 to 1970. The distribution of these values is positively skewed, the mean being 6.0 percent and the median 4.0 percent. Compared with similarly computed values in the literature (Dickinson and Whiteley, 1970), these index values for the Cam catchment confirm that the basin does not generate much rapid runoff at any time of the year.

These initial analyses suggest rather strongly that most of the area of the catchment which is covered by Boulder Clay deposits must be relatively permeable material since if it were tight and impermeable considerable surface runoff would be generated, resulting in higher annual and monthly runoff volumes.

2.2 Morphometric indices

A summary of some morphometric parameters of the Cam catchment is presented in Table 1. Regions exhibiting the most impermeable drainage characteristics include Debden Water, Fulpen Slade, and the headwaters of Wenden Brook (see Figure 1). The remaining major portion of the catchment displays tributary patterns exemplary of extremely limited surface runoff conditions.

The proportion of effectively impermeable area reflected by the geomorphologic pattern indexed above appears to be seven to ten percent. This area is concentrated in the headwaters above Saffron Walden, with a small portion on the western watershed. In general, such a pattern is in accord with the volumetric response observed in the preceding section.

2.3 Soil moisture storage

The data obtained monthly from the various soil moisture observation sites have been examined with regard to variability in time and space. As the sites were initially selected to be representative of the mapped soil conditions (see Figures 1 and 2), and located under similar grassed vegetation, it was anticipated that similarities and/or differences in soil moisture storage conditions might be observed.

For each of the seven sites for which soil moisture measurements were collected during the interval 1967 to 1970, a field capacity profile has been estimated. These profiles (Figure 3) were determined from field measurements obtained during the winter months of December to March before which no precipitation had been observed for at least five days. The variability between such sets of measurements at each site was found generally to be within sampling error, and the resulting profiles are thought to be representative of field capacity conditions.

Figure 3 reveals that, except for sites A and G, the estimated profiles are remarkably similar. Site A, located in the channel alluvium, might be expected to behave uniquely. On the other hand, the almost constant "shift" of six to eight percent moisture volume fraction exhibited by site G is

TABLE 1 MORPHOMETRIC PARAMETERS OF THE CAM CATCHMENT

Sub-basin	Stream Length (km)	Area (km^2)	First Order Streams	1st Order Streams per Unit Area	Median Area 1st Order Stream (km^2)	Drainage Density (km/km^2)	Stream Junctions per unit area
Northern Region	8.75	30.3	3	0.099	2.52	0.289	0.099
Western Region	15.34	19.5	3	0.154	3.62	0.787	0.102
Midland Region	11.76	39.1	0	0	-	0.301	0.102
The Slade	16.40	21.6	6	0.278	2.46	0.759	0.231
Fulpen Slade	11.62	8.5	7	0.824*	0.53*	1.367*	0.704*
Debden Water	10.91	10.4	5	0.481*	0.89*	1.049*	0.383*
Southern Region	19.97	27.9	9	0.323	1.67	0.716	0.251
Wenden Brook	15.19	22.5	6	0.267	0.55*	0.675	0.178
Wicken Water	10.56	17.2	2	0.116	7.74	0.614	0.058
Total Area	120.51	197.2	41	0.208	1.22	0.611	0.183

*Indices indicating regions with the most highly developed surface drainage system.

thought to be peculiar to the site and not necessarily representative of the soils in the area. As the neutron probe has not been calibrated for each individual site, it is possible for estimated moisture volumes to be in error due to installation or site peculiarities.

Considering the variability of soil conditions discussed in the Introduction, the similarities in Figure 3 seem remarkable. Although the seven soil moisture observation sites represent a small sample of the soils in the catchment, nevertheless the above results further suggest that some of the Chalk and Boulder Clay areas store moisture in a similar way.

Correlations between observations at the various sites and an areal weighted mean for the catchment reflect the similarities observed above. Although the Mole Hall location, site E, was found to be the best correlated, there was very little to choose between sites B, D, E, and F, located in both Chalk and Boulder Clay.

2.4 Groundwater levels

Observations discussed in the preceding sections suggest that, from a hydrological response point of view, much of the area of the Cam catchment which is characterized by a superficial Boulder Clay deposit may behave similarly to regions of bare Chalk. That is, the manner in which regions generate direct runoff and store soil moisture appears similar. Consideration is now given to the groundwater system in order to study the recharge, storage, and outflow patterns from the saturated zone.

Water table contour maps (Figure 4) have revealed the possible existence of a regional groundwater flow system and allowed the following observations to be made: (i) the regional water table divide generally coincides with the surface topographic divide; (ii) water table gradients over much of the area are similar; and (iii) the groundwater system discharges along the central river course.

With the possible exception of the southern edge of the catchment, the water table divide corresponds to the physiography. Further, the flow lines tend to converge on the outlet section near Dernford Mill. At the southern end, the water table gradient becomes very flat and the groundwater divide

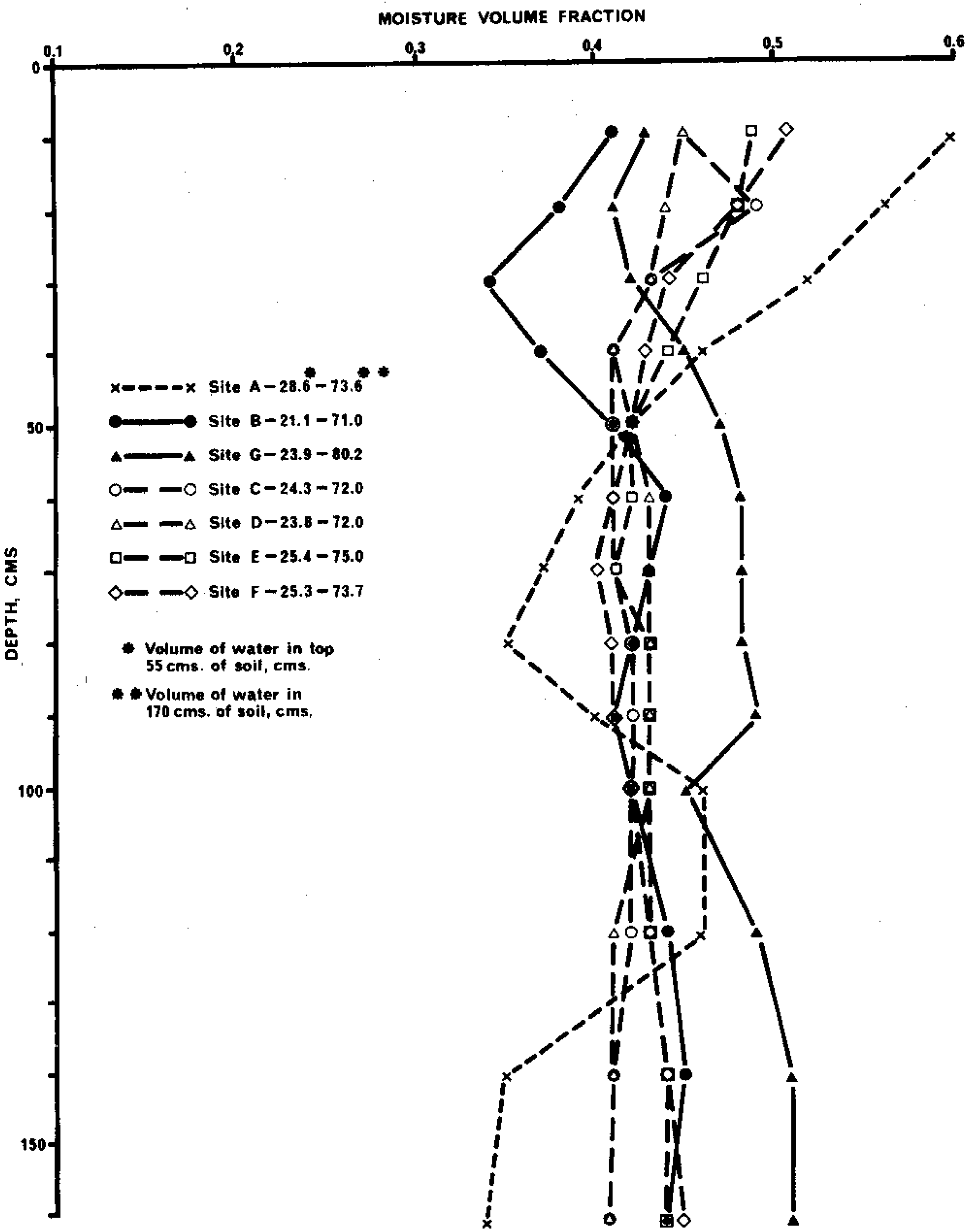


FIGURE 3 ESTIMATED FIELD CAPACITY PROFILES FOR SOIL MOISTURE OBSERVATION SITES

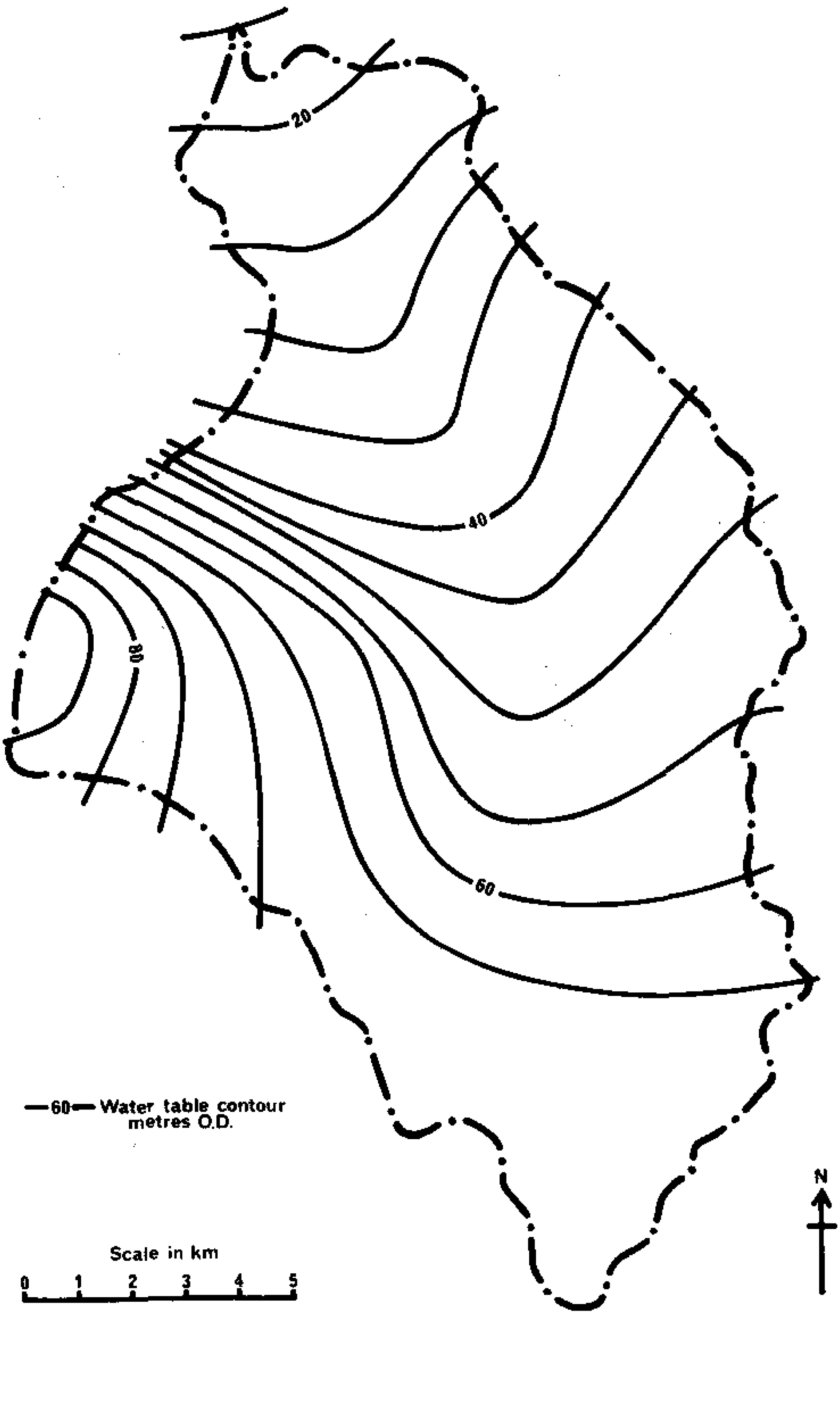


FIGURE 4 WATER TABLE CONTOURS FITTED BY EYE FOR DATA OF MARCH 25th, 1969

ill-defined. Data from wells in the vicinity suggest that the divide may in fact shift its position seasonally (Figure 5). However, as the gradients are particularly level, seepage into or out of the catchment is likely to be of negligible volume.

A similarity in water table gradients over much of the catchment area implies that recharge to the groundwater system and transmissibility through the saturated zone are somewhat uniform. In small areas, where there are local irregularities in surface conditions, soils and the Chalk, this statement is undoubtedly invalid.

The appearance of steep gradients in the northwest of the catchment coincides with the escarpment. A similar concentration of low transmissibility has been observed in a like location to the east of the Cam catchment (Woodland, 1946). It is suggested that such zones might have been the result of the way in which the Chalk strata were folded.

Examination of the water table contour maps in conjunction with the topographic map reveals the major groundwater discharge region (Figure 6). This region appears to be continuous along the main stream channel, implying that all tributaries to this channel are likely to become dry during the summer months. As is to be expected, the discharge region of Figure 6 corresponds closely to the region of maximum water well yield mapped by Woodland (1946).

In addition to their variability in space, the well levels were considered with regard to their fluctuations in time. Although the range of seasonal fluctuation can vary substantially from one observation site to another, all wells generally peak at the same time in March or April, and reach a low together in October or November. No lag between wells near the divide and those in the valley is apparent, nor between those beneath Boulder Clay and bare Chalk. Recharge to the water table, therefore, seems to occur similarly in time throughout the basin. The wells exhibiting the greatest fluctuations in water level are located in the zone of low transmissibility.

2.5 Groundwater storage and outflow

In order that estimates could be made of the volume of groundwater

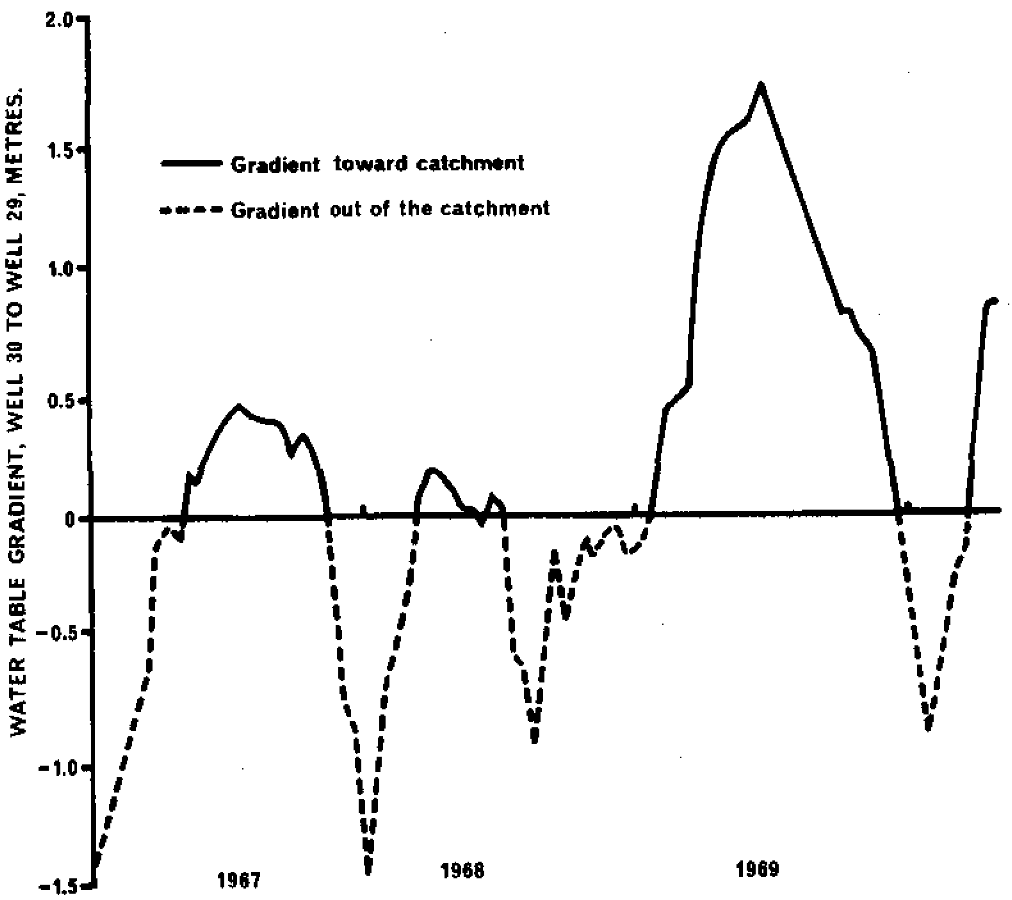


FIGURE 5 CHANGES IN WATER TABLE GRADIENT AT SOUTHERN END OF CAM CATCHMENT

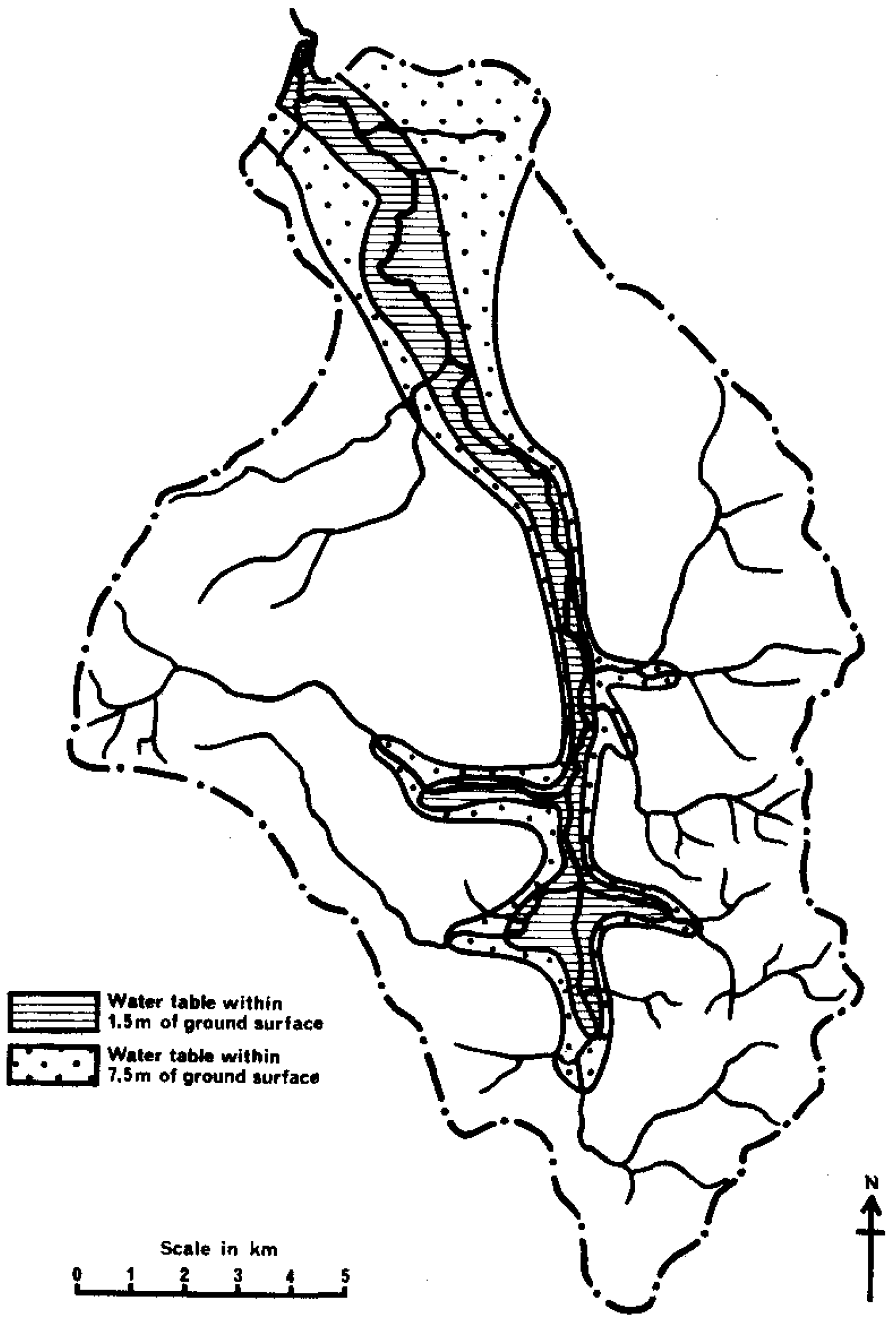


FIGURE 6 GROUNDWATER DISCHARGE REGION OF THE CAM CATCHMENT

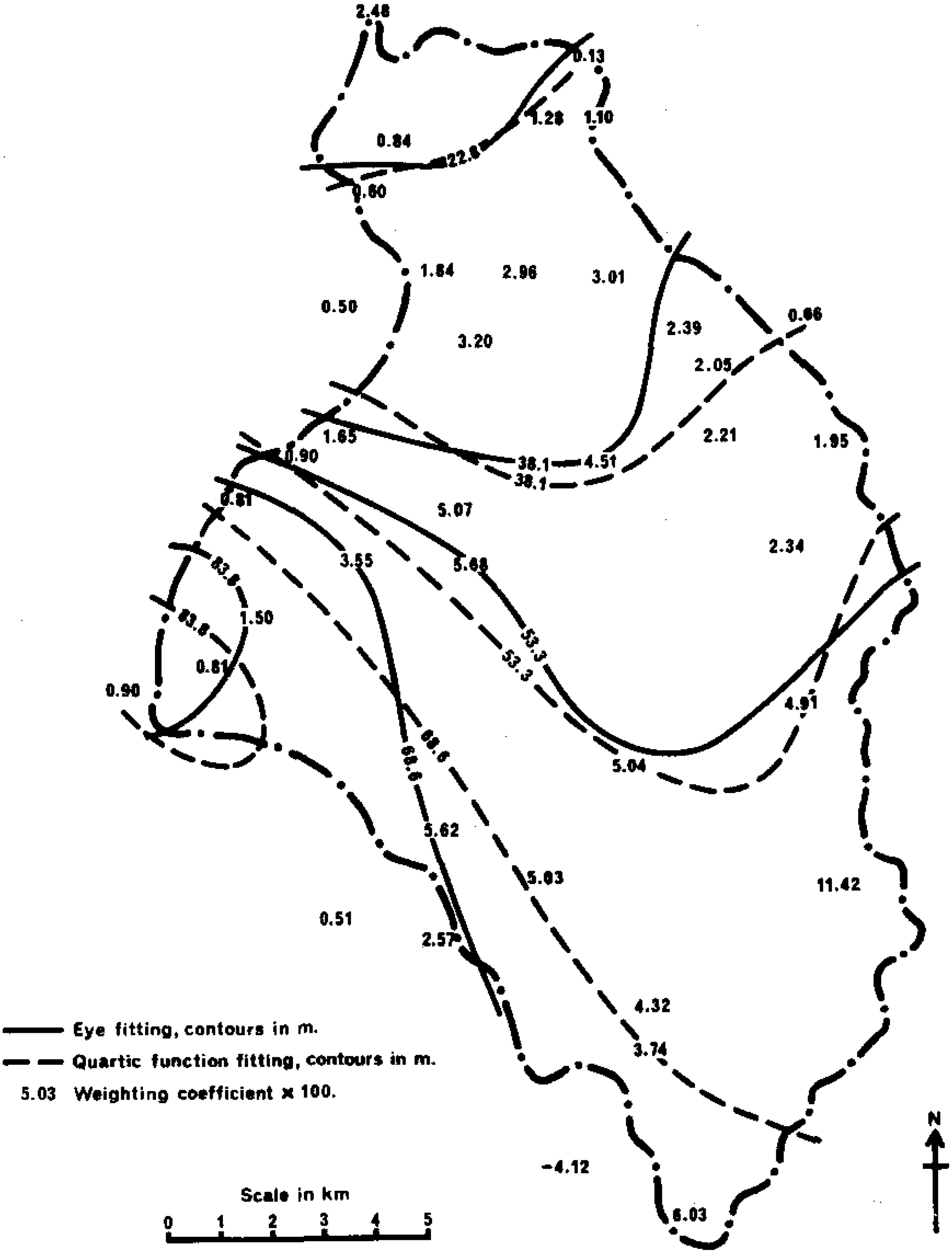


FIGURE 7 COMPARATIVE WATER TABLE CONTOURS FITTED BY EYE AND A QUARTIC SURFACE FOR MARCH 25th,1969

stored in the catchment, a quartic surface was fitted to each set of water level measurements. A mean water table level was then determined at two weekly intervals, employing a set of weighting coefficients for 38 well sites to facilitate the volumetric integration (Chidley and Keys, 1970). A comparison of the quartic and eye fittings to a set of data is shown in Figure 7, along with the weighting coefficients which may be applied to the appropriate well levels to determine a basin mean water table level.

A comparison of the basin mean water table level estimated from the quartic surface and from an arithmetic average is presented in Figure 8. Observation points appear to be sufficiently numerous and widely distributed in area that differences in level from date to date are essentially identical, irrespective of computation procedure. Storage changes estimated by arithmetic mean tend to be four percent larger than those yielded by the integration method.

Changes in the mean water table level, itself an index of the groundwater storage condition over the catchment, were considered together with estimated groundwater runoff volumes during the summer months to determine an effective porosity, or storage coefficient, for the saturated zone. For the data selected (i.e. during periods of little or no groundwater recharge) the base flow volume should approximate the change in groundwater storage. The slope of Figure 9, therefore, is an estimate of the storage coefficient. If it could be assumed that there were no seepage or evaporation losses during the time intervals considered, and that the estimates of storage change and runoff were without error, then the line used for determining the storage coefficient would be a lower envelope of the measured points. However, in the light of the data and computations used, the line was sketched as shown.

The storage coefficient having been estimated to be 2.4 percent, a water balance of the groundwater system was performed, for which continuity was expressed,

$$GPR - GRO = GS$$

where GPR is the recharge volume to groundwater in a given time interval,

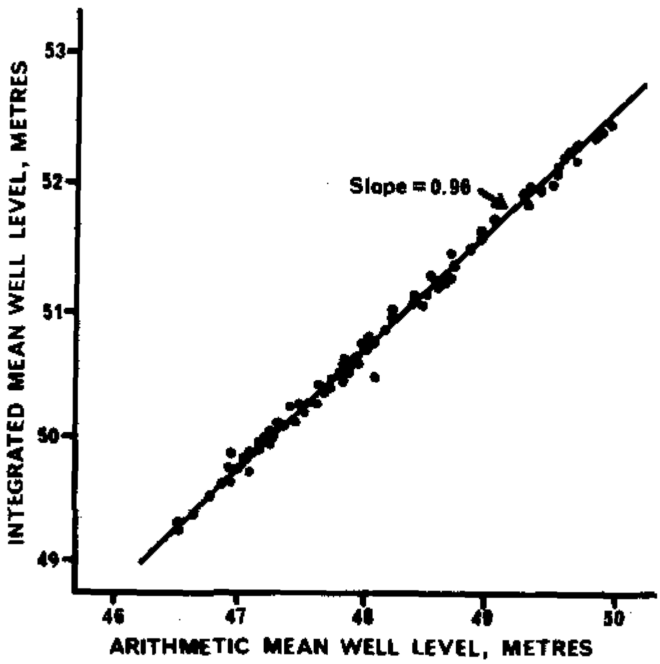


FIGURE 8 MEAN WATER TABLE LEVEL COMPUTED BY INTEGRATION OF QUARTIC SURFACE PLOTTED AGAINST THE ARITHMETIC AVERAGE WELL LEVEL

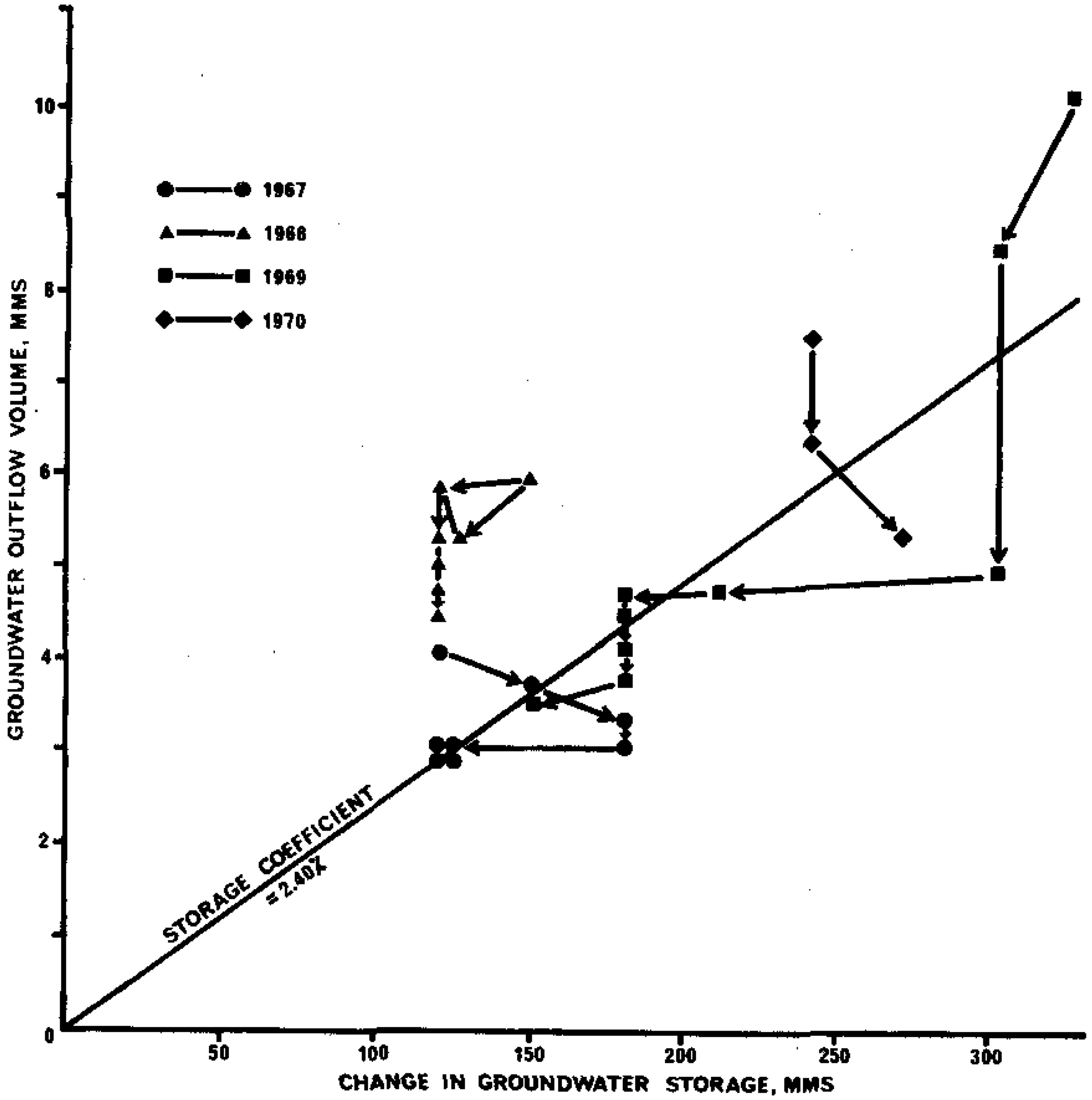
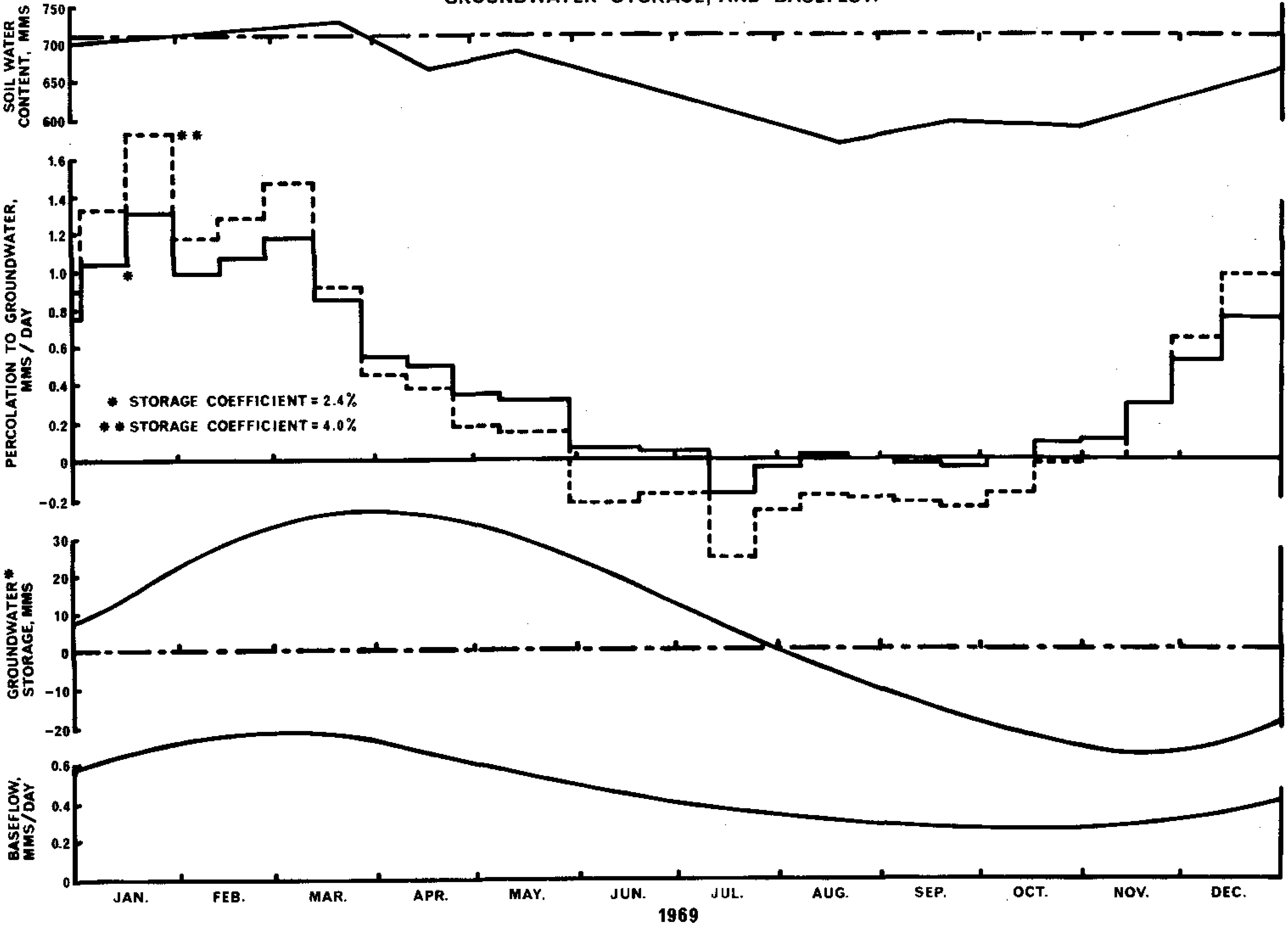


FIGURE 9 ESTIMATION OF STORAGE COEFFICIENT FROM GROUNDWATER WATER LEVEL AND OUTFLOW DATA

FIGURE 10 SAMPLE SEASONAL PATTERNS OF SOIL WATER CONTENT, PERCOLATION TO GROUNDWATER, GROUNDWATER STORAGE, AND BASEFLOW



GRO is the groundwater outflow volume in the same interval, as estimated from the streamflow hydrograph,

GS is the change in groundwater storage, estimated from the mean water table levels and the storage coefficient.

The patterns of recharge, storage and outflow determined in the balance are illustrated in Figure 10. Soil moisture observations have been included for comparison, along with recharge, or percolation, estimated from a storage coefficient of four percent.

Figure 10 reveals two items of particular interest. Firstly, an increase in storage coefficient to four percent changes the pattern of seasonal recharge, but does not alter the annual volume. Secondly, the groundwater outflow hydrograph anticipates rather than lags the groundwater storage condition. Each item is considered further below.

The use of a storage coefficient of 2.4 percent results in the estimation of essentially no recharge during the summer months of 1967, 1969 and 1970, with continuous recharge throughout 1968. An increase in storage coefficient to 4.0 percent reduces the summer recharge in 1968 to a negligible amount, but results in a requirement for negative recharge during the other three summers. Such negative values could be meaningful either if seepage out of the catchment into adjacent basins were to occur at such times, or if substantial evaporation were to take place from the groundwater system. It seems likely that if any seepage occurs across the catchment boundary during the summer seasons, it is into rather than out of the Cam Catchment (see Figure 5). Further, as the water table is a considerable distance below the ground surface in all but the immediate discharge region of the main stream, large amounts of evaporation from the groundwater system seem unlikely. Therefore, on the basis of seasonal recharge pattern, a storage coefficient of 2.4 percent appears realistic.

For values of storage coefficient in the range of those already mentioned, annual recharge totals are very similar, as revealed in Table 2. For such patterns of recharge, the annual volume is not a sensitive indicator of an appropriate storage coefficient.

It is also useful to consider at this point the relative magnitude of

TABLE 2. RECHARGE ESTIMATES DETERMINED FROM GROUNDWATER BALANCE

Time interval	Recharge to groundwater (mms over catchment) Storage coefficient of 2.4 percent	Storage coefficient of 4.0 percent
6th Jan 1967 to 3rd Jan 1968	136	139
4th Jan 1968 to 3rd Jan 1969	186	201
3rd Jan 1969 to 8th Jan 1970	150	133
9th Jan 1970 to 26th June 1970	124	143

TABLE 3. RECHARGE RATES REQUIRED TO YIELD ESTIMATED VOLUMES FOR STORAGE COEFFICIENT OF 2.4 PERCENT

Time interval	Recharge rate to groundwater (mms over catchment area noted) Area of 91 km^2	Area of 155 km^2	Area of 197 km^2
6th Jan 1967 to 3rd Jan 1968	295	172	136
4th Jan 1968 to 2nd Jan 1969	404	236	186
3rd Jan 1969 to 8th Jan 1970	326	190	150
9th Jan 1970 to 26th June 1970	269	157	124

the annual recharge volumes. Table 3 shows the annual recharge rates required if uniform percolation were assumed to take place over 91 km^2, 155 km^2 and 197 km^2, and no percolation existed over the remainder of the catchment. The first area is approximately equivalent to that of the bare Chalk; the second may be obtained by considering the total area less 18 km^2 of groundwater discharge region and less 23 km^2 of effectively impermeable soil; the final figure is the catchment area. The recharge values presented, when regarded with previous estimates of 150 to 180 mms percolating through bare Chalk annually (Woodland, 1946), tend to confirm the notion that at least 155 km^2 of the catchment behave as permeable recharge area.

The manner in which groundwater outflow precedes, or anticipates, storage is curious! This relationship is also demonstrated in Figure 11 by the strong clockwise hysteresis effect. This hysteresis is essentially removed if the baseflow is plotted against the mean well levels lagged by four weeks, as shown in Figure 12. A second approach to removing the hysteresis is to consider the storage to be a linear combination of recharge and baseflow, shown in Figure 13.

The "backward lag" between groundwater storage and baseflow has also been observed by Hunter Blair (1965). His explanation of this phenomenon was based on a bank storage hypothesis, causing flow to (i) begin to rise before the main catchment storage had begun to increase, and (ii) begin to decline before storage had achieved its peak. As the water table well levels discussed earlier revealed no lag tendency in space, the above hypothesis appears as acceptable as any, although it can neither be proven nor disproven with the available data.

Figure 12 also reveals that, although a linear relationship may exist between recharge, storage and baseflow, the storage axis may shift during excessively wet or dry years. If such shifts do occur in time, possibly reflecting the filling up and depletion of secondary storage systems, modelling of the groundwater storage system becomes extremely tenuous.

2.6 Conclusion from process observations

Information on general volumetric response, geomorphology, soil

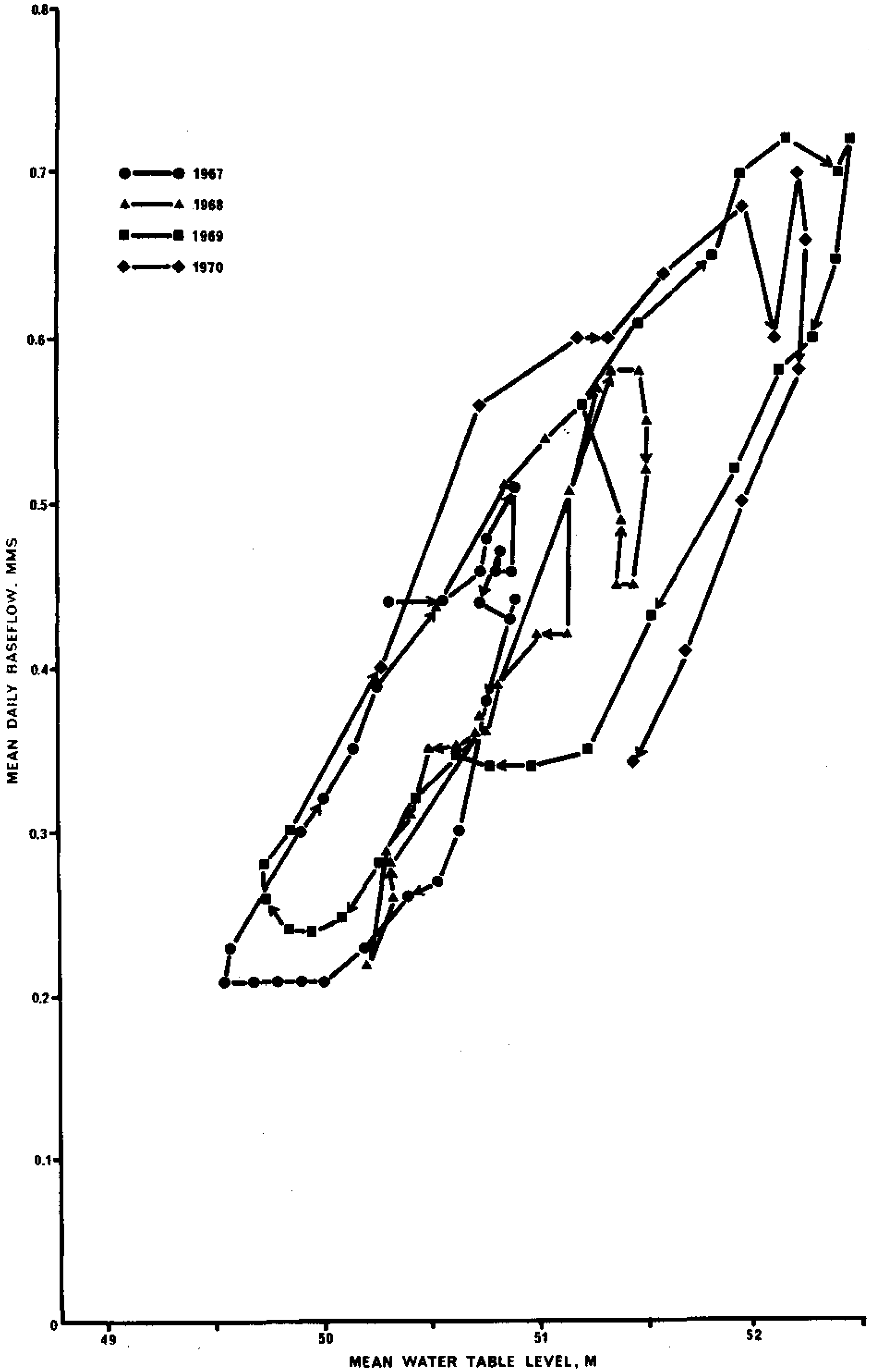


FIGURE 11 RELATIONSHIP BETWEEN BASEFLOW AND MEAN WATER TABLE LEVEL

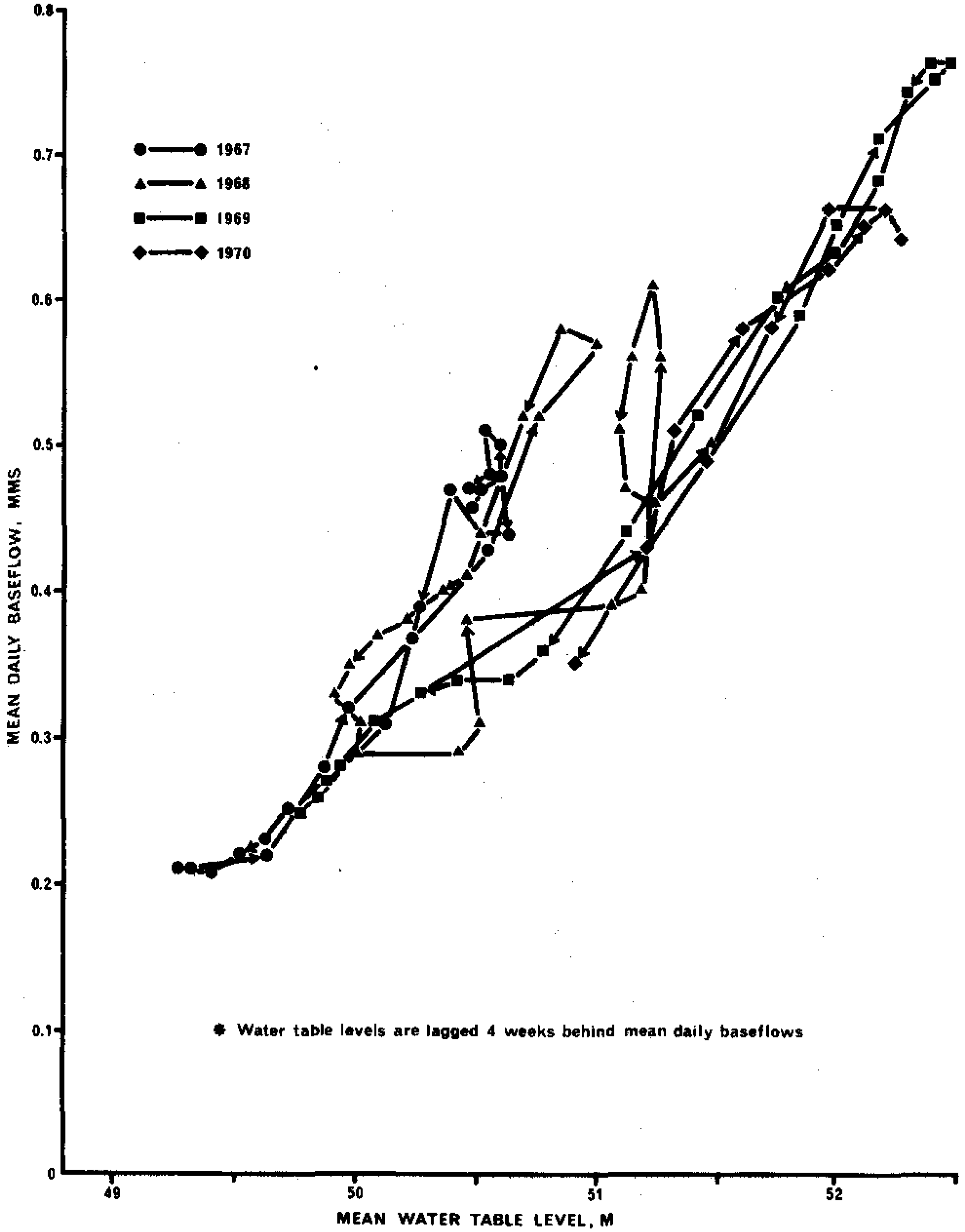


FIGURE 12 RELATIONSHIP BETWEEN BASEFLOW AND LAGGED WATER TABLE LEVEL

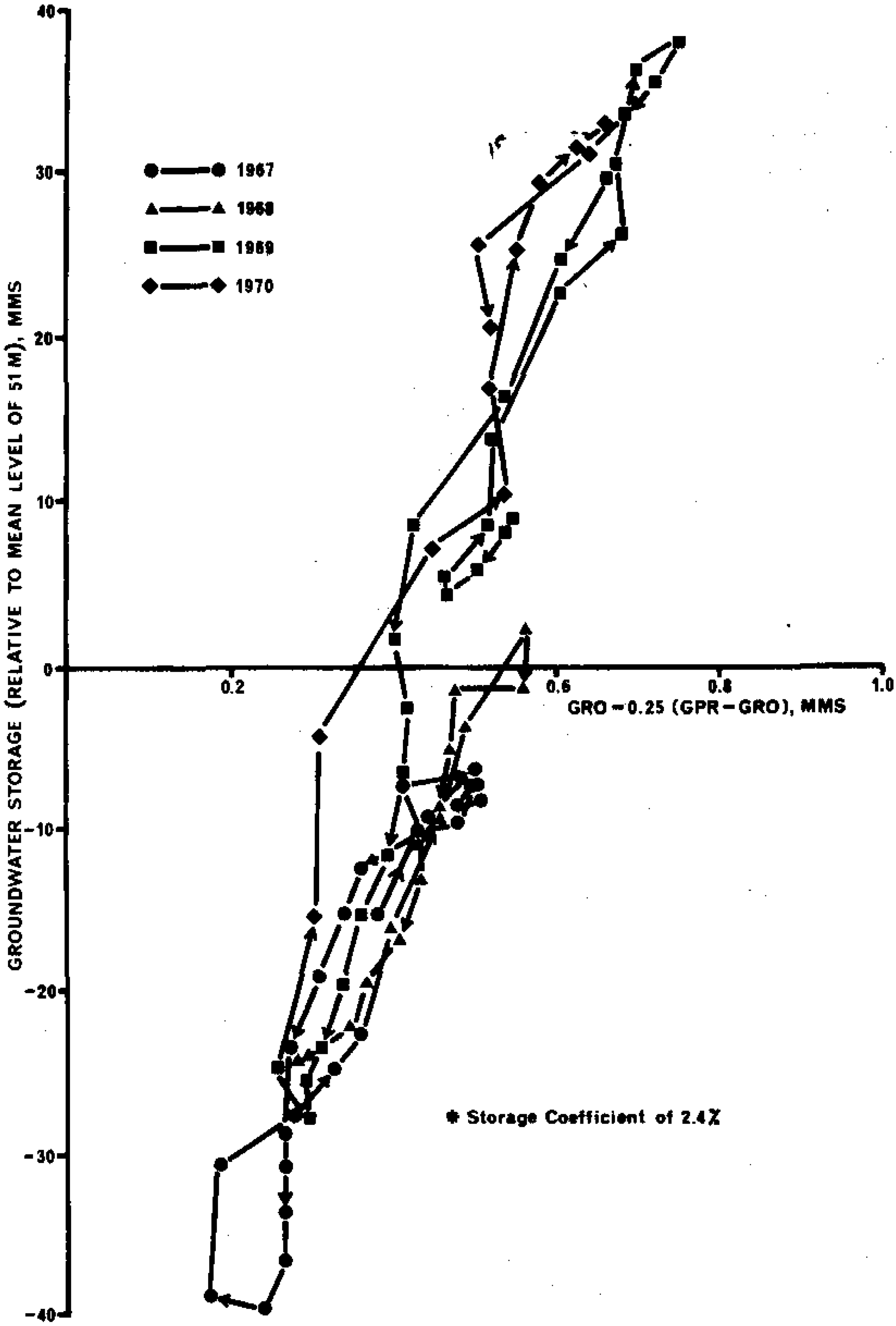


FIGURE 13 GROUNDWATER STORAGE AS A LINEAR FUNCTION OF RECHARGE AND BASEFLOW

moisture and groundwater suggests that the Cam catchment is predominantly a highly permeable area. There is no indication that the Boulder Clay deposit as a whole behaves differently from regions of bare Chalk. Further, the characteristics of the Chalk appear uniform over much of the catchment. As water storage and transmission properties may be similar in many areas of the basin, it is concluded that the Cam catchment may be considered as a single homogeneous region for the purpose of modelling hydrologic response.

3. DEVELOPMENT OF CONCEPTUAL MODELS

3.1 A lumped model

On the basis of the preceding analysis, a lumped model (i.e. lumped in space) has been hypothesized for the Cam catchment. The model is conceived as three storage systems, as illustrated in Figure 14. The nature of each system and the characterization of fluxes into, between and away from each system are discussed below.

a) Surface store

The surface storage component accepts the incoming rainfall and potential evaporative demand and calculates effective rain and a residual evaporative demand to be passed on to the soil moisture store, after subtracting evaporation from the surface store. The precipitation entering the store, RAIN (II) is described by 6-hourly precipitation totals obtained from the raingauge network (see Section 1.3). The potential daily pan evaporation, EVAP (II), is estimated from the climate station data and apportioned into 6-hourly intervals with the weighting factors 0.697, 0.138, 0.0, and 0.165 for the periods 09-15, 15-21, 21-03 and 03-09 hours respectively. Evaporation from the surface store, ES, is assumed to be a function of the potential evaporation, EVAP (II), and the effective rain discharged to the soil moisture store, ERAIN, a function of the incoming precipitation, and the surface storage moisture status, SS-DS.

b) Soil moisture store

Three hydrological processes are conceived to be associated with the soil

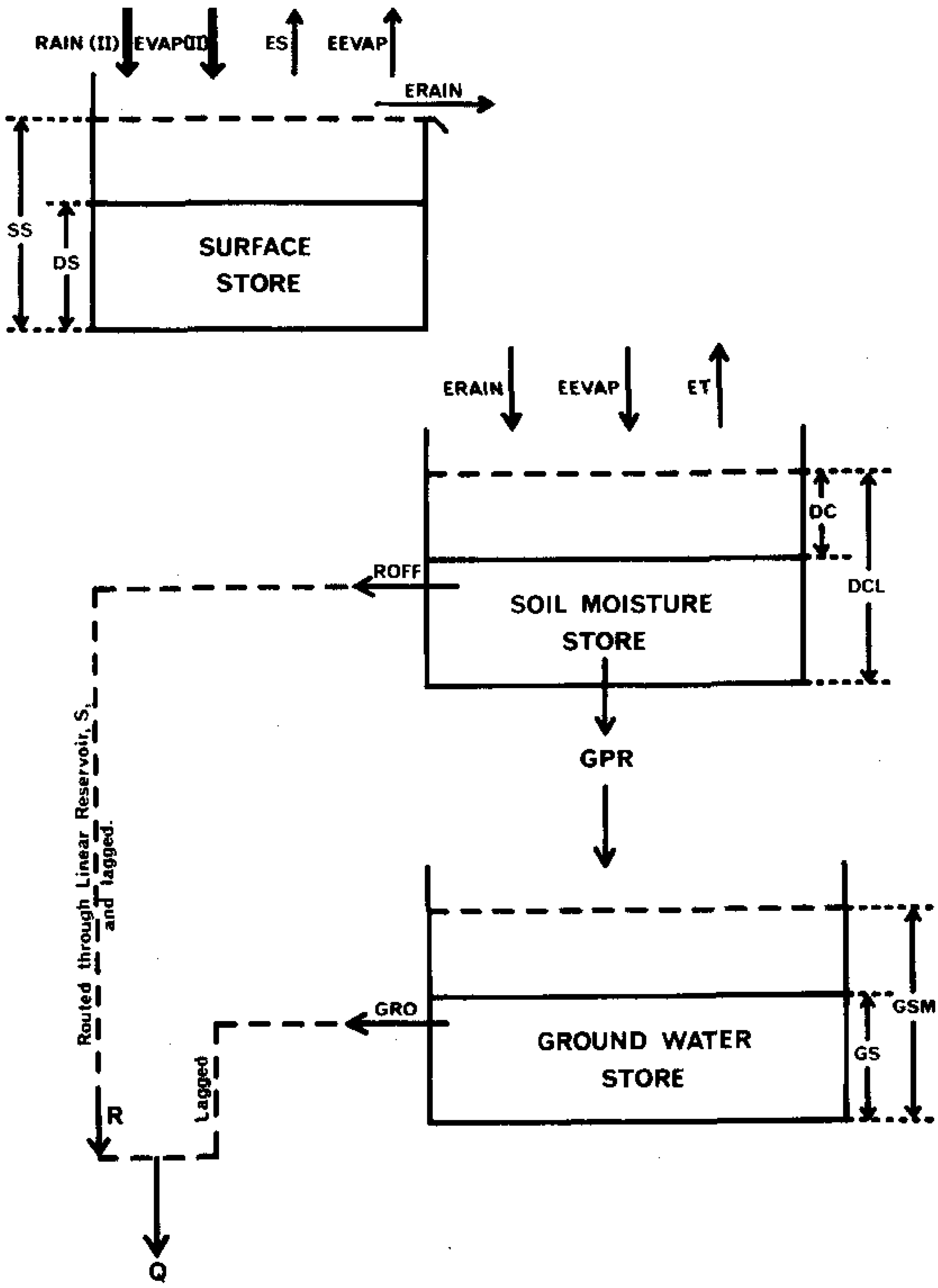


FIGURE 14 THREE STORE CONCEPTUAL MODEL FOR CAM CATCHMENT

moisture storage component. These are actual transpiration, direct runoff and percolation to the groundwater store. Actual transpiration is assumed to be a function of the evaporative demand on the soil moisture store, EEVAP, and the moisture status of the store, DC. The evaporative demand is that not satisfied by the surface store. Direct runoff, ROFF, and percolation to groundwater, GRP, are also characterized as simple functions of the soil moisture storage.

c) Groundwater store

Storage in this component of the system is assumed to be a function of input to the store, GPR, and output, GRO. A simpler form relating only storage and outflow has also been considered. The moisture status of the store is monitored as GS.

d) Routing of runoff values:

The direct runoff volume, ROFF, is routed through a single linear reservoir of storage, S, and lagged by a time interval, DEL, to produce the direct runoff contribution. The routed direct runoff, R, is then added to the groundwater outflow component, GRO, which may be lagged by the interval GDEL, to yield the estimated six-hourly outflow Q.

The various functional forms utilized in the model are outlined in Table 4. Some of the relationships are presented graphically in Figure 15.

3.2 Optimisation of parameters

The error function, or residual variance, has been defined as the cumulated sum of squares of difference between computed and observed six-hourly runoff increments. That is, $F^2 = \sum_{1}^{n} (Q' - Q)^2$. The efficiency was considered as the proportion of the "no model" variance accounted for by the model, $R^2 = (Fo^2 - F^2)/Fo^2$, where Fo^2 was the "no-model" residual variance (Nash and Sutcliffe, 1970).

The four years of record, 1966 to 1969, were divided into two equal periods of two years' duration. Various forms of the model were optimised on the

TABLE 4 FUNCTIONS USED IN VARIOUS MODEL FORMS

	Model 1	Model 2	Model 3	Model 4
Surface store	1 Effective rainfall ERAIN=RAIN(II) + DS-SS	→	→	→
	2 Evaporation from surface ES=FS. EVAP(II)	→	→	→
	3 Residual evap. demand EEVAP=EVAP(II) - ES	→	→	→
	Parameters: FS, SS	→	→	→
	Constraints: FS=1.0	→	FS not constrained	→
Soil moisture store	4 Actual transpiration ET=ECP.EEVAP where $ECP=FC \frac{(DCT-DC)}{(DCT-DCS)}$	→	→	→
	5 Direct runoff generation ROFF=ROP.ERAIN where ROP=RC/(RS+DC)	→	→	$ROP=RC.e^{-RS.DC}$
	6 Percolation to groundwater $GPR=GLR\ (1.0 - \frac{DC}{GDM})$	→	→	→
	Parameters: FC, DCT, DCS, RC, RS, ROM, GLR, GDM	→	→	ROM deleted
	Constraints: $ROP \leqslant ROM$	→	→	No contraints
Groundwater stores	7 Flow from groundwater GS=GSM.GRO	GS=GSM [GF.GPR +(1-GF).GRO]	→	→
	Parameters: GSM	Parameters: GSM, GF	→	→
Routing of runoff volumes	8 S=DRK.R and R delayed by DEL	→	→	→
	GRO delayed by GDEL	No delay of GRO	→	→
	Parameters: DRK, DEL, GDEL	GDEL deleted	→	→

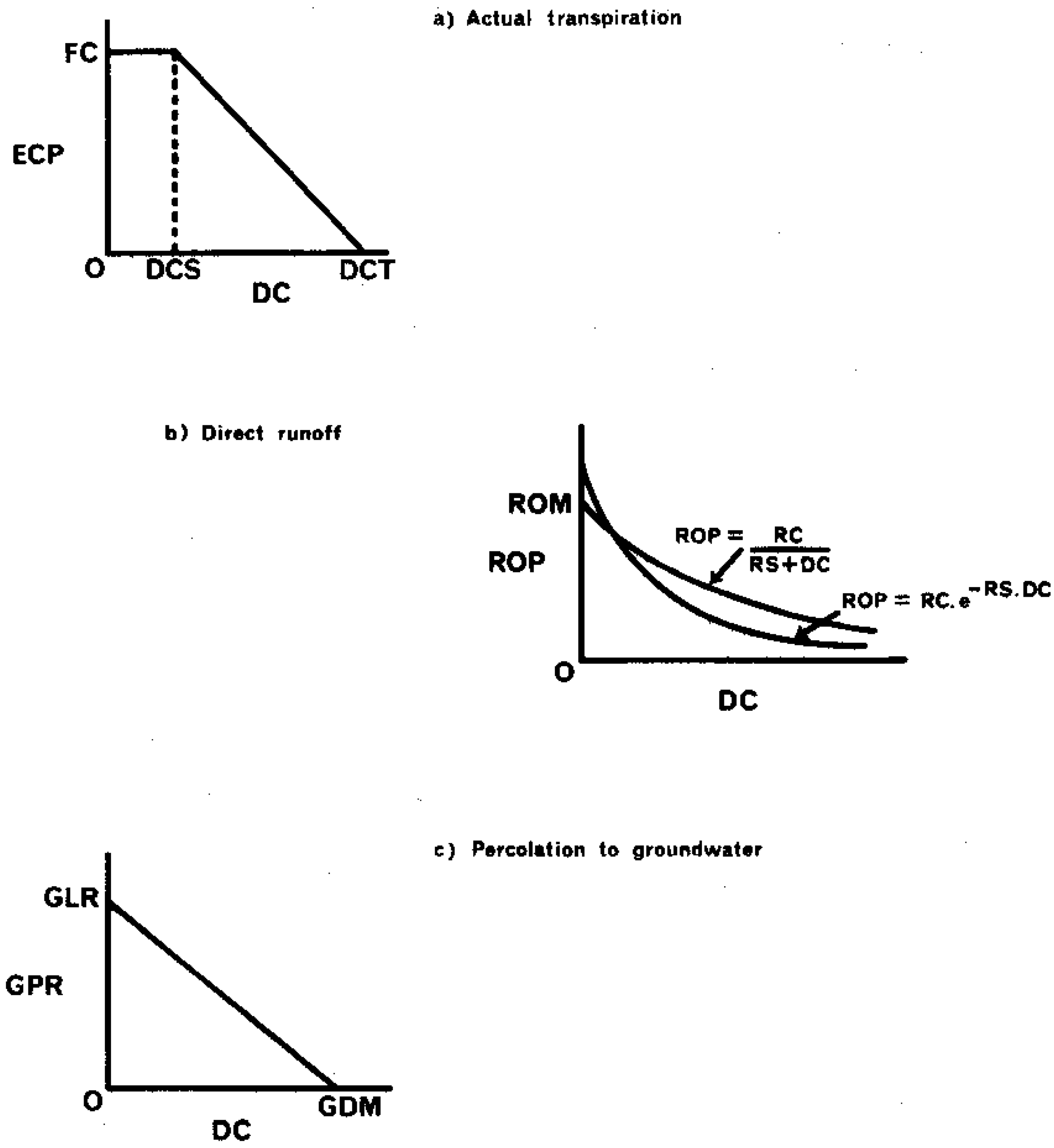


FIGURE 15 GRAPHICAL REPRESENTATION OF MODEL FUNCTIONS RELATING TO SOIL MOISTURE STORE

first two years' record, and the residual variance, efficiency, and optimised parameter values were noted. A final form of the model was then applied with a set of optimum values to the next two years of data to obtain a second and independent assessment of residual variance and efficiency.

The optimisation process used was that of O'Connell *et al* (1970). Instead of optimising all parameters simultaneously, groupings of up to eight parameters were optimised while the remainder were fixed at seemingly appropriate or previously optimised values. In the light of existing interdependence among parameters, this approach, utilized in conjunction with the mapping of the error function for various combinations, proved efficient and economical.

The various functional forms of the model presented in Table 4, optimised for the 1966-1967 period of record, yield the results shown in Table 5. The set of parameter values listed for Model 5 was subjectively selected, after inspection of the earlier optimised values and mappings of the error function.

Regarding the general "goodness of fit" of predicted flows to those observed, the higher numbered models appear to describe groundwater flow conditions adequately but to encounter difficulty with the direct runoff. Further, the problem with direct runoff appears to be associated more with the time distribution than with the occurrence and volume of flow. Generally, the observed hydrograph is more peaked than the predicted flow record. These observations may be noted in the sample period of observed and predicted flows sketched in Figure 16.

3.3 Interdependence of parameters

As noted by Mandeville *et al*, (1970), the optimisation and utility of particular model parameters can most easily be studied if the parameters are othogonal (i.e. a change in one does not involve a change in another). Unfortunately, such orthogonality is not generally experienced in hydrological conceptual models and interdependence of parameters commonly increases with the number of parameters.

TABLE 5 SETS OF OPTIMISED PARAMETER VALUES, WITH RESPECTIVE INDICES OF EFFICIENCY AND VOLUME ERROR

Parameter	Model 1	Model 2	Model 3	Model 4	Model 5
SS	14.3	14.3	9.29	9.5	9.5
FS	1.0	1.0	1.42	1.4	1.5

FC	0.65	0.65	0.65	0.65	0.60
DCS	16.86	16.86	16.86	16.86	17.0
DCT	128.60	128.60	104.5	104.5	100.0

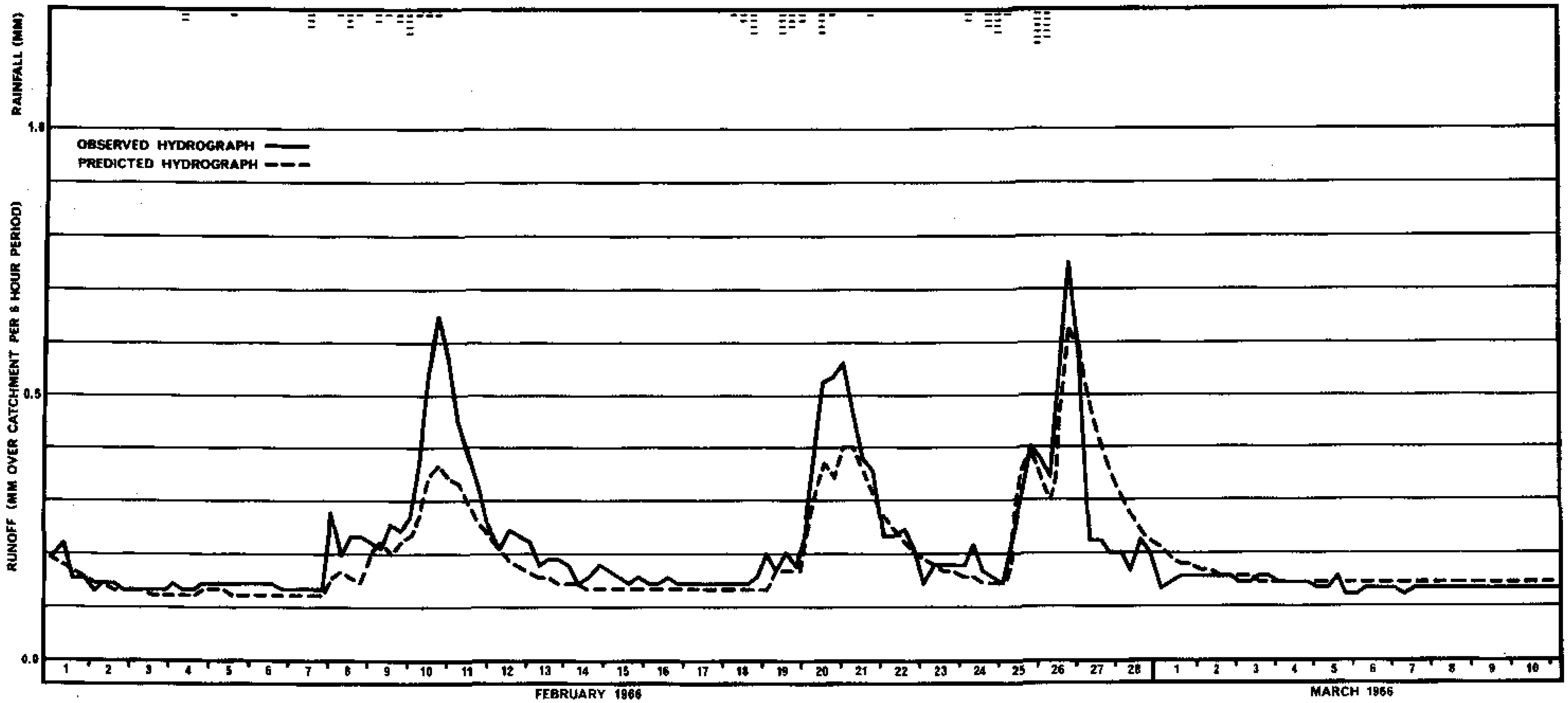
RC	4.40	4.40	4.5	0.24	0.24
RS	18.92	18.92	15.0	0.029	0.029
ROM	0.30	0.30	0.20	-	-

GLR	0.27	0.27	0.27	0.27	0.28
GDM	50.0	57.54	57.54	57.54	65.0

GSM	100.0	600.0	539.5	539.5	560.0
GF	-	-0.15	-0.13	-0.13	-0.075
GDEL	4.0	-	-	-	-

DEL	2.32	2.32	2.32	2.32	2.32
DRK	4.85	4.85	4.85	4.63	4.55
Efficiency as a percentage	61	72	76	77	78
Error in runoff volume as a percentage	+ 4.2	+ 1.8	- 0.19	- 0.66	+ 1.5

FIGURE 16 SAMPLE RECORD OF OBSERVED AND PREDICTED RUNOFF VALUES



A considerable range of interdependence conditions was found to exist in various portions of the model forms considered above. Sample mappings of the error function, presented in Figures 17 to 22, reveal the situation. Such mappings were found to be very useful as guides to the selection of an optimum set of parameter values.

The highest interdependence was observed among the parameters concerning the surface store and evaporation from the soil moisture store. The parameters are not only dependent within each of these storage phases, but also between phases. For a catchment in which 70 percent of the incoming annual precipitation is evaporated, it is perhaps to be expected that all parameters involving evaporation should be highly interdependent.

The parameters describing the surface store and actual transpiration are conceived together as modelling the total evapotranspiration process. For the present, they seem difficult to interpret physically. What a surface store of approximately ten mms capacity physically characterizes, and whether evaporation from agricultural surfaces occurs at one and a half times the potential rate, remain unanswered questions. In fact, the FS and SS parameters may merely describe a black box which suitably disposes of moisture for the rest of the model.

The parameter DCT tends to assume a value such that evaporation from the soil moisture store is possible at all times. That is, DCT coincides with the largest soil moisture deficit experienced in the period of record. Whether such a condition indicates continuous evaporation from the soil, or whether it reflects the need for a modelling mechanism to evaporate considerable volumes of water, is open to speculation.

The direct runoff, percolation and groundwater storage parameters are reasonably independent and more amenable to physical interpretation. Although the error function surface for the direct runoff parameters, RS and RC, is relatively flat, there is a clearly defined optimum. These parameters appear to be fairly stable when other parameter values are modified. The range of runoff percentages yielded by the RS and RC values obtained are comparable with those identified in Section 2.1.

Figures 21 and 22, showing error function contours for percolation

ERROR FUNCTION SURFACES FOR THE EVAPORATION PARAMETERS OF THE MODEL

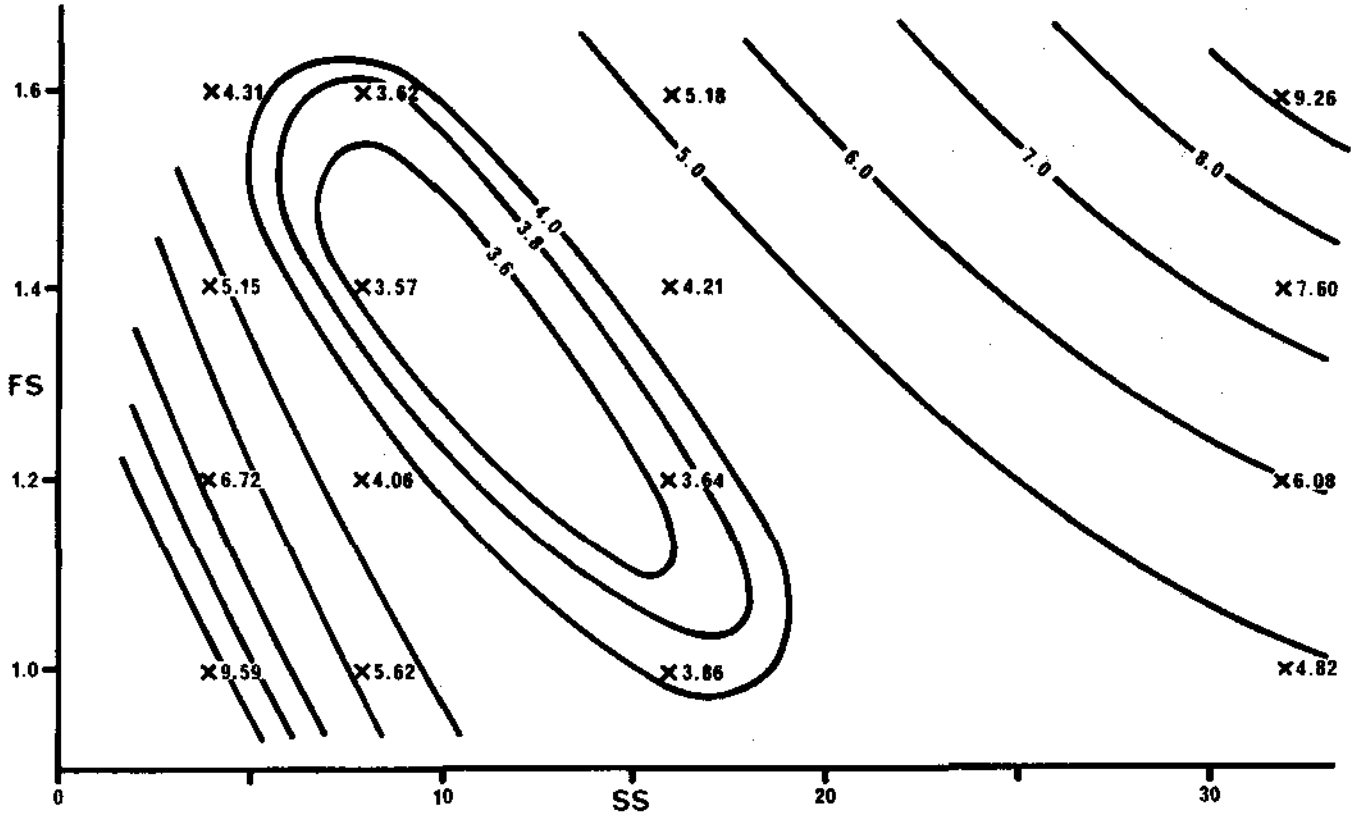


FIGURE 17 THE FS/SS SURFACE

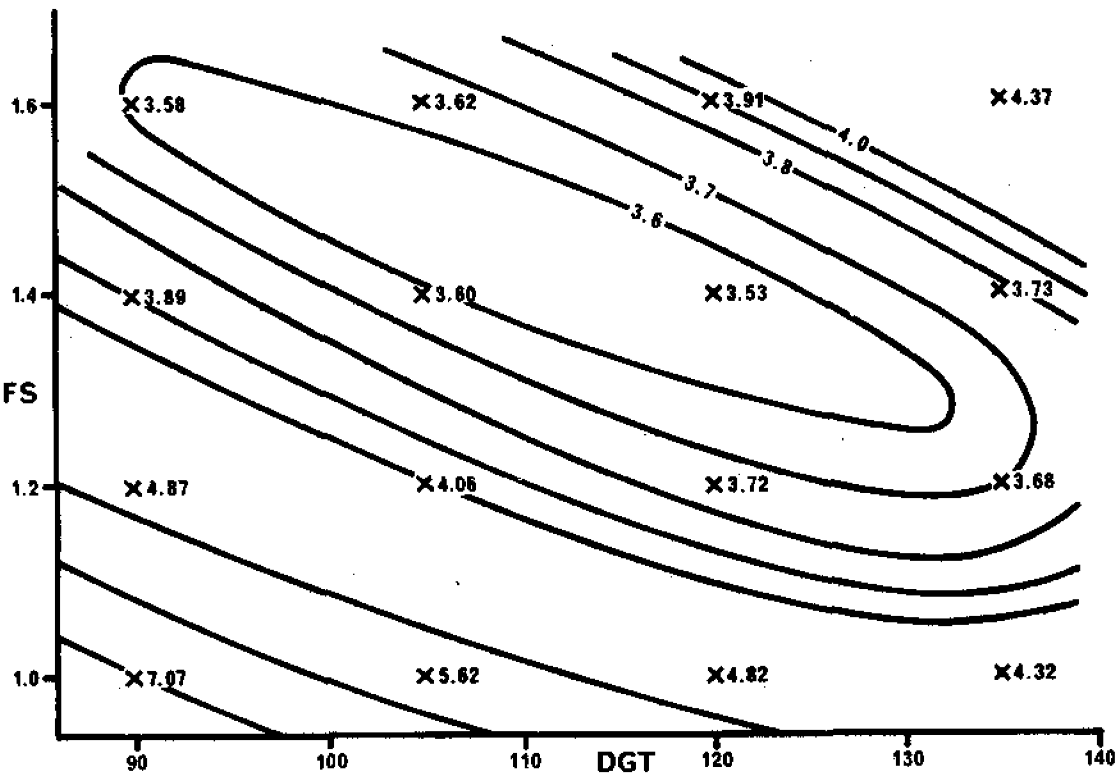


FIGURE 18 THE FS/DGT SURFACE

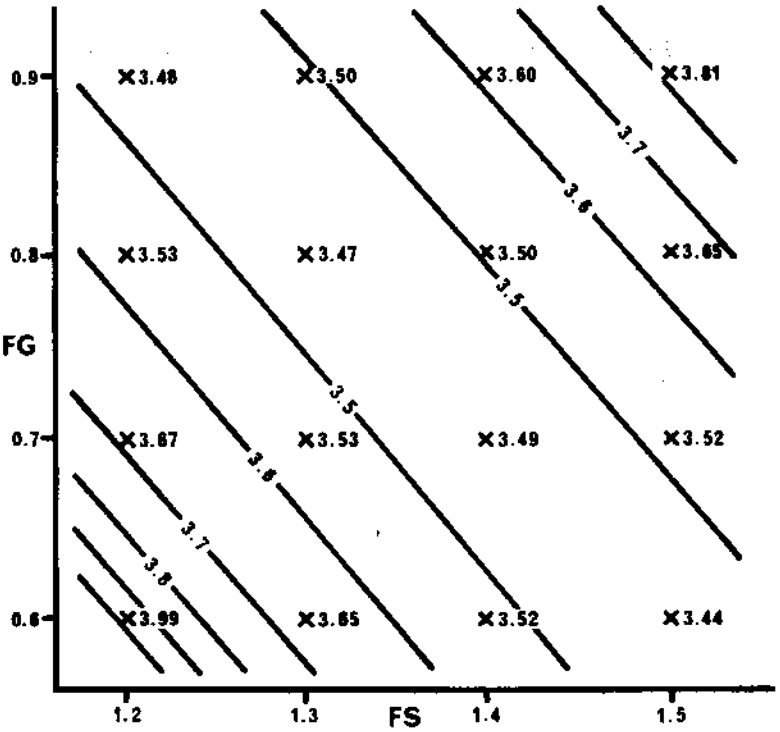


FIGURE 19 ERROR FUNCTION SURFACE SHOWING INTERDEPENDENCE BETWEEN THE TWO EVAPORATION REDUCTION FACTORS

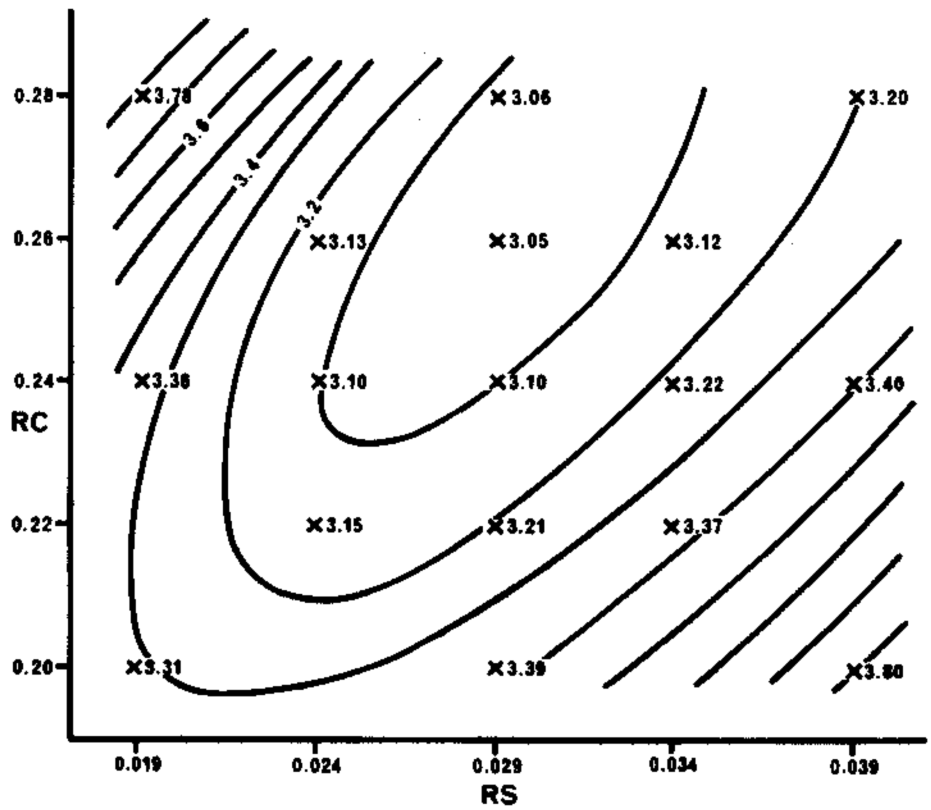


FIGURE 20 INTERDEPENDENCE BETWEEN THE SURFACE RUNOFF GENERATION PARAMETERS $(ROP = RC/e^{DC \times RS})$

ERROR FUNCTION SURFACES FOR VARIOUS GROUNDWATER PARAMETERS

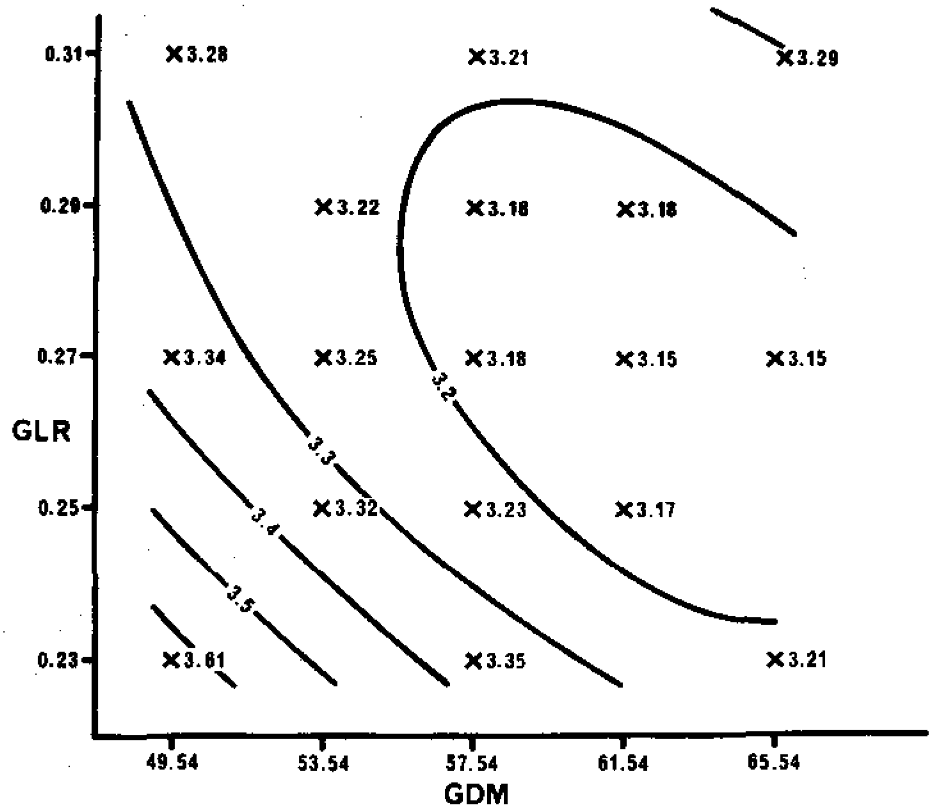


FIGURE 21 THE GLR/GDM SURFACE SHOWING INTERDEPENDENCE BETWEEN PARAMETERS IN THE PERCOLATION MODEL

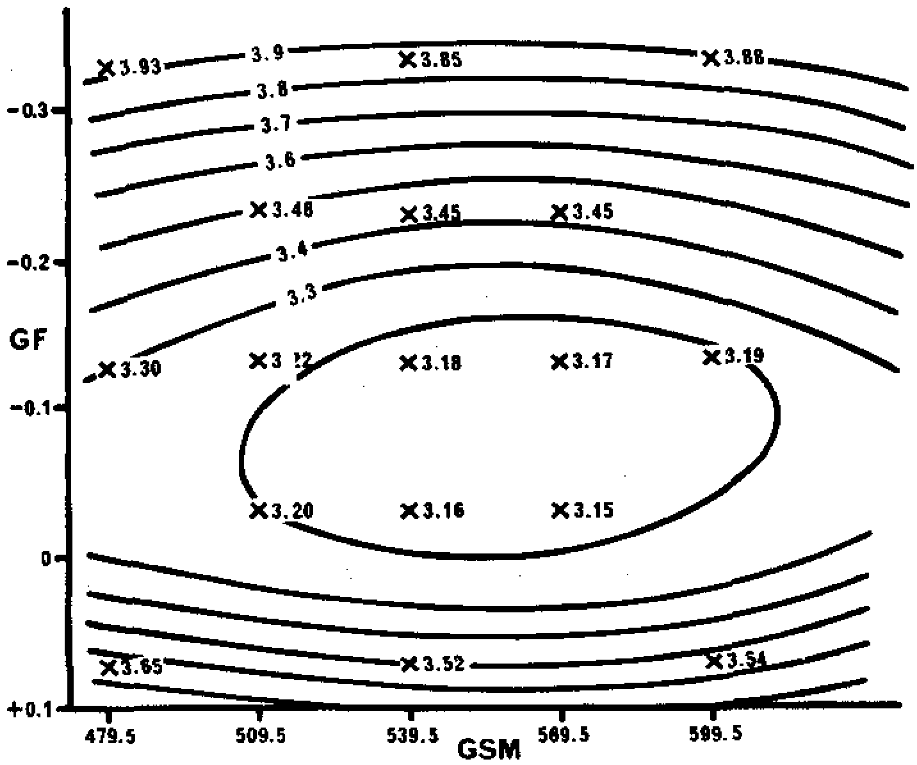


FIGURE 22 THE GF/GSM SURFACE SHOWS THE LOW SENSITIVITY OF THE GROUNDWATER RESERVOIR COEFFICIENT, GSM

and groundwater storage parameters, are both relatively flat. In the former an optimum is relatively clear; in the latter, the optimum of GF is clear, while the error function is less sensitive to GSM. A suitable value of GSM may be obtained from consideration of well level and baseflow data such as that of Figure 13. The parameter GLR may correspond to a physically based maximum rate of percolation through the upper horizons.

3.4 Prediction test

Having obtained an optimum set of parameter values from the 1966-1967 period of record (i.e. Model 5), the model was used to predict flows given rainfall and evaporation, for 1968 and 1969. Indices of the goodness of fit are given in Table 6 and a comparative plot of discharges is presented in Figure 23. The results of such a prediction test the utility of the model.

As the flow during 1968 and 1969 was considerably more variable than in 1966 and 1967, as shown in the "no-model" variance terms, a final optimisation of the direct runoff parameters RC, RS and DRK was performed on the total four years of record. The resulting values were 0.267, 0.026 and 0.152 respectively. As noted above, the RC and RS parameters remained stable; however, the DRK parameter changed significantly. The corresponding changes in efficiency are shown in Table 6.

The model has predicted baseflow in 1968 and 1969 as well as it did in 1966 and 1967. This is reassuring, as some earlier results (Section 2.5) suggested the possibility of a somewhat unstable groundwater system. As a consequence of an adequate baseflow fit, errors in volume remain fairly small.

On the other hand, prediction of a suitable distribution of direct runoff is difficult to achieve. It is worth noting that the low efficiency obtained in 1968, and the change in DRK resulting in an improved efficiency relate to a single major flood event in September of that year. The remainder of the record is insignificantly affected.

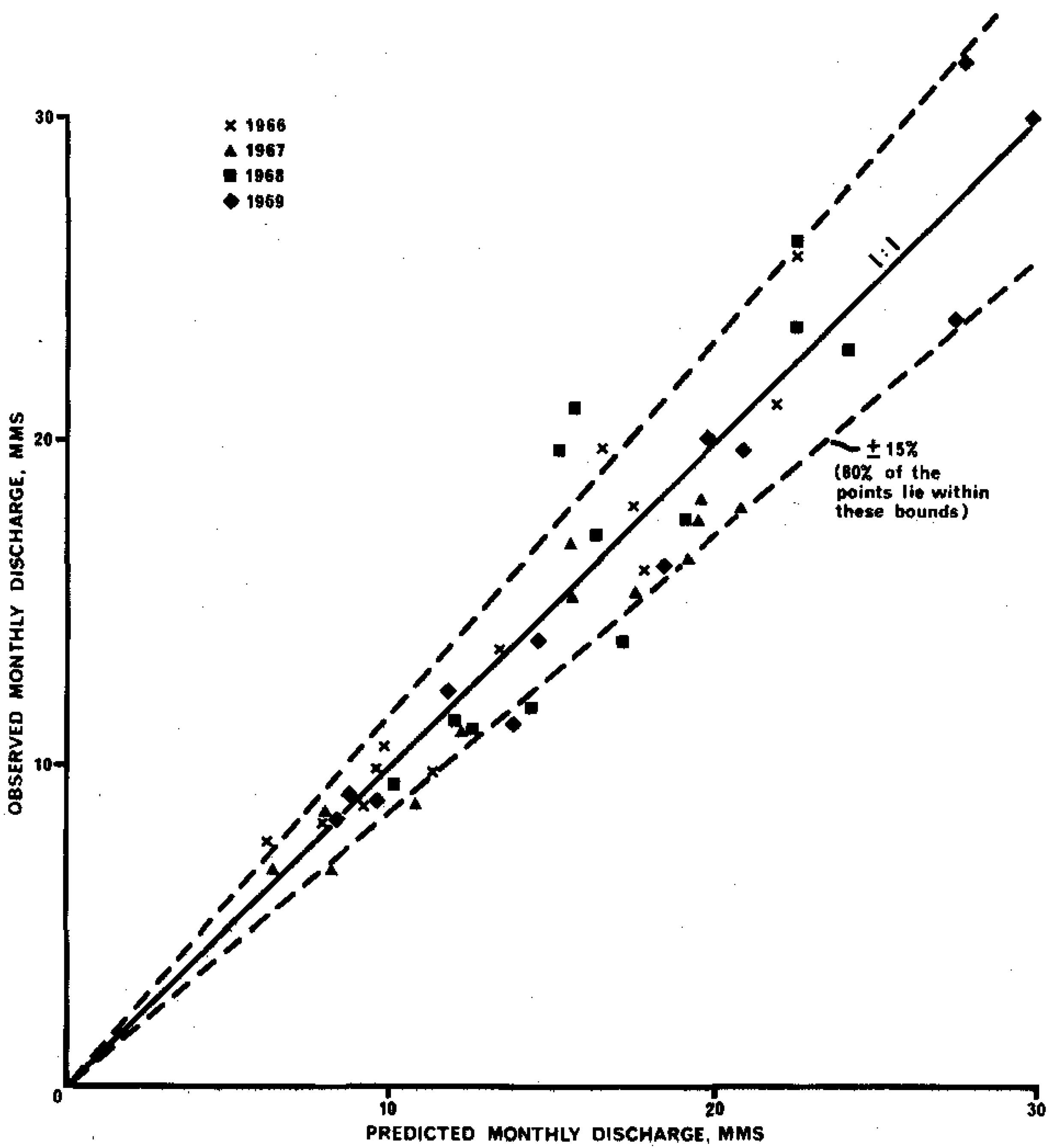
TABLE 6 GOODNESS OF FIT INDICES

Period of record	Annual "no-model" variance	Test run 1*		Test run 2**	
		Annual efficiency	Percentage error in runoff volume	Annual efficiency	Percentage error in runoff volume
1966	8.59	77.9	- 4.6	75.6	- 2.95
1967	5.47	78.1	+ 8.1	78.1	+ 9.10
1968	15.83	67.2	- 2.0	75.4	- 1.58
1969	13.05	73.9	+ 3.7	74.0	+ 3.83

*Model optimised on 1966-1967 record and utilised for prediction during 1968-1969.

**Parameters RC, RS, and DRK optimised on the four years of record.

FIGURE 23 PREDICTED AND OBSERVED MONTHLY DISCHARGES FOR 1966-1969



4. CONCLUSIONS AND COMMENTS

The Cam catchment has been observed to behave hydrologically as an extremely permeable area. Regions of superficial Boulder Clay deposit and bare Chalk appear to behave in surprisingly similar fashions with regard to their generation of direct runoff, storage of moisture and ability to recharge the groundwater system. The behaviour of the saturated flow regime indicates that much of the Chalk stores and transmits moisture rather uniformly, exhibiting a storage coefficient of approximately 2.5 percent.

The lumped conceptual model hypothesized for the catchment predicts the baseflow response both in volume and time distribution quite adequately during wet and dry periods. This result is most encouraging for the utility of the model for general water resources management. Further, if more detailed studies of the groundwater regime were to be considered, the model might be used to generate a uniformly distributed recharge input.

For the purpose of predicting the time distribution of flood events, the model is less satisfactory. Whether problems in this area are associated with the behaviour of the surface store component and/or the routing portion is not clearly understood. These two aspects of the model, also the most difficult to interpret physically, warrant further thought and modification.

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