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Effect of Local Ground Slope on the Performance of Tile Drains in a Clay Soil

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The hydrograph response of tile drains laid in a heavy clay soil on a convex slope is described. Drainage efficiency is shown to be inversely related to local ground slope, with short-term storm outfall on a 5·0% slope only 0·55 that on a 3·6% incline. Peak drain discharge is also inversely related to ground slope, particularly during winter when water contents are high. However, the drain hydrograph shows a quicker response to rainfall on steeper slopes. The time of concentration is reduced by 1·5 h for every 1% increase in ground slope. This differential behaviour of tile laterals serves to indicate the pathways taken by rainwater once it enters the soil. Desiccation cracks are used to bypass the topsoil in autumn. But once the soil has been swollen by autumn rain, plough-layer interflow becomes a more significant route for drainage. Water passes to the drainage installation down the looser soil overlying the tile laterals or down persistent cracks left by the leg of the mole plough after lateral flow within the topsoil. The catchment of an individual tile drain is shown to be inversely related to local ground slope, at least in winter. This is due to the drainage divide shifting upslope in response to increasing slope gradient. In convex situations this results in a loss of contributing area on the downslope side of the lateral that is not compensated for by commensurate gains on its upslope side. Short-term drainage efficiency, that is the percentage of incident rainfall which is removed as drainflow within 40 h, falls from 82 to 45% as slope increases from 3·6 to 5·1%. Since the object of a drainage installation is rapid evacuation of rainwater, this unexpected effect of local ground slope in reducing drain efficiency has considerable significance for the design of underdrainage schemes in undulating topography.

1. Introduction

The aim of installing a drainage scheme in agricultural soils is to lower the water table, and thereby improve the rooting conditions of crop plants particularly during winter months. Control of the soil water regime also brings benefits in the form of more machinery work-days, especially in the critical spring and autumn cultivation periods when correct timing of operations is essential to avoid soil damage (Wind,[1] Thomasson[2]).

Previous studies of the efficiency of drainage installations in clay soils have generally avoided sites with complicated topography and have been conducted on level or uniformly sloping ground (for example Childs,[3] Benoit and Bornstein,[4] Trafford and Rycroft,[5] Robinson and Beven,[6] Leeds-Harrison *et al.*[7]). While the choice of ground with simple surface morphology is a pre-requisite in evaluating the efficiencies of different drainage configurations, it means that little attention has been paid to the effect of local differences in ground slope on the character of tile drain outfall. Trafford[8] indicates the beneficial effects of laying interceptor drains at the foot of steeper sloping areas in clay soils where ponding and surface run-off can be prevented. Rands[9] suggests that an increase in ground slope produces a flashier tile drain outfall hydrograph, but gives no details.

The artificial drainage of sloping land requires a consideration of both the shallow movement of water in the plough layer and deeper seated interflow (van Hoorn and van der Molen[10]). However, detailed studies of the effects of different groundslope on water movement have been confined so far to laboratory simulation experiments (Bouwer,[11] Carlson,[12] Zeigler[13]). In this paper, we explore the efficiency and response of field installations, relating these to local ground slope and to the relative position of tile drains in a convex topography.

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2. Experimental site

2.1. *Soils and drainage methods*

The experiment was carried out on a surface water gley soil (a Haplaqualf) developed over Eocene London Clay. A detailed survey reported by Parkinson[14] indicates remarkable uniformity of soil properties in the fields under consideration. Typical clay contents vary from 24% in the A horizon to 42% in the B horizon. The clay fraction is dominated by kaolinite (52%) and illite (47%) though there are traces of montmorillonite and vermiculite. Despite the low proportion of expansible clay minerals, the soil responds to dehydration by cracking. The fissures, both polygonal and those associated with the drawing of mole channels, extend well into the subsoil. The soil and its water regime have been described in detail by Reid and Parkinson.[15] Saturated hydraulic conductivity ranges from 10^{-3} m/s in the well structured topsoil to 10^{-6} m/s in the subsoil.

In order to investigate the influence of local ground slope on drainflow the outfalls of six tile drains (laterals labelled L1 to L6) were monitored over a period of four drainage seasons, from October 1977 to June 1981. The drains had been installed in 1975, two years before measurement began and were laid in a fashion typical for this soil type. This is at a regular spacing of 40 m and at a depth of 0·9 m. The drain trench was back-filled to within 0·4 m of the surface with flint gravel, and mole channels were drawn in the direction of greatest slope at 2 m spacing and 0·6 m depth to connect with the permeable fill (*Fig. 1*).

The contour pattern shown in *Fig. 1* is typical of the basal portion of valley slopes in British clay lowlands. Gradient increases downslope to give a convex profile. Ground slope over the catchment area of each monitored tile lateral was established by transecting survey lines at 10 m intervals along each drain. Mean values are given in Table 1. It can be seen that the range is from 3·6 to 5·1%. The contributing area of each drain is also given in Table 1. But these are identified notionally on a plan basis only. The results of the monitoring programme will demonstrate clearly that this standard method of estimating catchment area is inadequate and does not explain observed drain discharges.

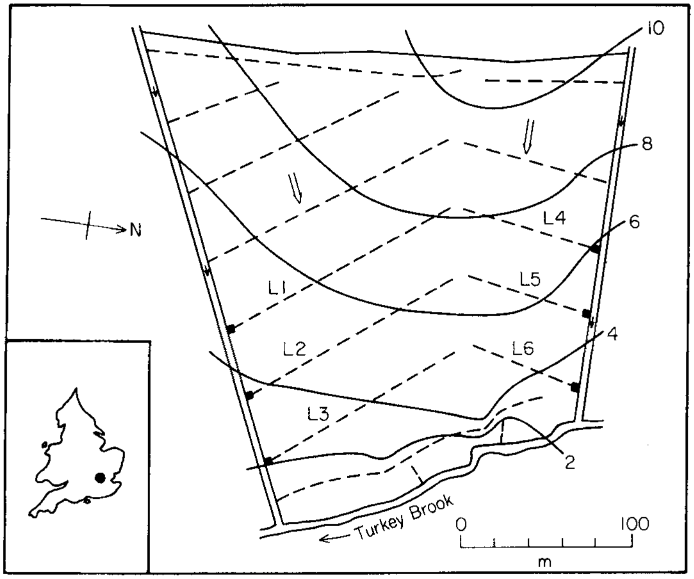

Fig. 1. Drainage installations and experimental instrumentation in Field 989, Rectory Farm, Enfield Chase, England (51°41′N, 0°06′W). ═ open ditch; --- tile drain; L1–L6 monitored tile laterals; ⟹ direction of mole drains; ■ flow measuring device and recorder; /4 contours in metres—arbitrary datum

Table 1
Physical characteristics of tile drains and their catchments

		Drain length, m	*Plan drainage area (notional catchment), m^2*	*Mean ground slope over drainage area, ± standard error %*
Tile Drain	L1	147	5485	3·6±0·1
	L2	138	5107	3·8±0·2
	L3	126	4414	4·8±0·3
	L4	85	3136	4·6±0·2
	L5	78	2915	4·5±0·3
	L6	73	2135	5·1±0·3

2.2. *Instrumentation*

Rainfall was recorded continuously by an autographic raingauge. Tile drain discharge was measured either with dynamically calibrated tilting buckets (in the case of L2, 4, 5 and 6; Fig. 1) or with "V" notch weir boxes (L1 and 3). By careful chart synchronization, an accuracy of better than ±0·08 h (5 min) has been achieved in deriving temporal hydrograph parameters (Reid and Parkinson[16]). Soil water content was determined at a maximum of 11 sites using a "Wallingford" neutron probe below 20 cm and thermogravimetric analyses for the topsoil.

3. Results and discussion

3.1.1 *Classification of drainflow events*

During the four years of recording, there were 215 storm rises in the hydrograph. These have been divided into two major groups according to soil moisture conditions antecedent to rainfall: the *winter group* incorporates all storms (totalling 150) which occurred when the soil was fully rewetted and moisture levels oscillated around a mean level which corresponded roughly to field capacity (Reid and Parkinson[16]); the *non-winter group* (65) includes those storms falling on a soil that had a moisture deficit—these were mainly autumn rainfalls. In fact, the drains ran in response to heavy rainfalls during periods that have a surprisingly large range of prevailing soil moisture deficits (SMD). In the autumns of 1977, 1978 and 1979 the first drain discharge occurred with SMD less than 50 mm. However, in October 1980, an extension of the summer period of high evaporation was followed by a 33 mm rainstorm which generated drainflow even though SMD stood at 179 mm. It is because of the important role played by desiccation cracks in the disposal of rainwater at this time of year, that these non-winter events have been analysed separately.

The winter group of storms has been further sub-divided into *simple winter hydrograph rises* (117) where the storm outfall is uncomplicated, and *secondary winter rises* (33) where a complex rainstorm may produce several drainflow peaks riding on the recession curve of the initial rise. This has been useful again in highlighting significant changes in the hydrological response of a soil that does not dispose of rainwater according to the classical redistribution models.

The length of record for each tile lateral under consideration varies according to the date of installation of the flow measuring device and to instrument failure. Generally, L1, L2 and L3 have a 4 year record, while L4, L5 and L6 were monitored over 2 years. In order to compare drain performance, the median values of the frequency distributions of each selected hydrograph parameter have been computed. It has also been necessary to express drainflow as discharge per unit drain length in order to eliminate differences in magnitude that are caused merely by unequal drain length.

3.2. *Ground slope and time of concentration of drainflow*

Water movement in the soil occurs in response to both gravitational and matric suction gradients. When matric suction tends to zero or becomes positive, as in winter months, it is the gravitational component that dominates flow processes. As a result, ground slope can be expected to have considerable influence over the hydrological response of a hillslope to rainfall at this time of year. In fact, the effects of small hollows and basins have been investigated (Anderson and Burt,[17] Lowery *et al.*,[18] Hanna *et al.*,[19] Reid and Parkinson[16]). But little attention has been paid to the influence of topographical convexity on the displacement of soil water, especially where drainage installations are involved. This is particularly surprising in view of the increasing awareness of potential flood hazard in drainage basins where a high percentage of the land has been subject to drainage improvements (Trafford,[20] Robinson and Beven[6]).

On the topographical convexity investigated here, local ground slope has been found to exert a strong influence on the lag between rainfall centroid and peak drainflow—the time of concentration, t_c (see *Fig. 2* for definitions of hydrological parameters used in this study). All three storm groupings—simple winter, secondary winter and simple non-winter—clearly indicate a reduction in the time taken for water to reach the tile drain as ground slope increases (*Fig. 2*). Although this, in itself, says nothing about the actual pathways taken by the water, it confirms in a convincing manner the pattern that might be expected from deductive reasoning of the influence of slope gradient on lateral flow of water in the soil, a pattern hitherto uncorroborated by field evidence.

In addition to flow through the soil, which is controlled in part by local ground slope, it was suspected that the time of concentration might also depend upon the time it takes water to pass

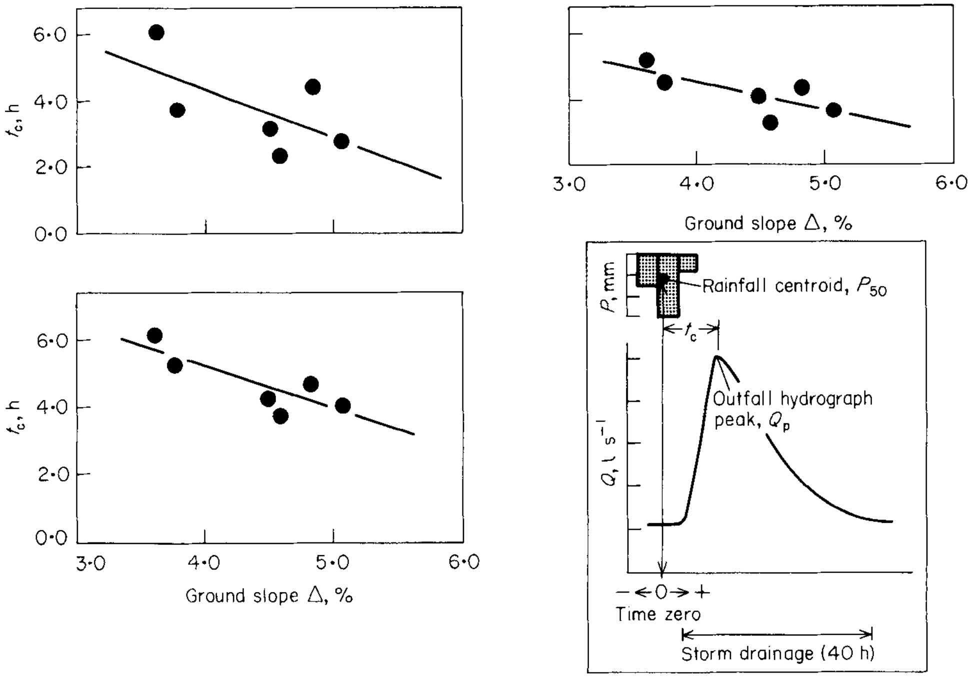

Fig. 2. Relationship between local ground slope (Δ) and median values of time of concentration (t_c) of the drain hydrographs. (Top left) simple winter storms, $t_c = 10{\cdot}13 - 1{\cdot}46\Delta$, $r = -0{\cdot}622$. (Bottom left) simple non-winter storms $t_c = 10{\cdot}19 - 1{\cdot}25\Delta$, $r = -0{\cdot}841$. (Top right) secondary winter storms, $t_c = 5{\cdot}28 - 0{\cdot}83\Delta$, $r = -0{\cdot}747$. The definition sketch (bottom right) describes the parameters used in this study where drain discharge, Q is produced in response to rainfall, P

down the tile drain itself. Times of travel in the drain were calculated using Manning's equation, assuming that the drain, with a roughness coefficient, n, of 0·0108 was running half-full. Even for L3, with the shallowest drain slope of 2·2%, water can flow from the furthest extremity of the drain to its outfall in less than 3 min. It was considered, therefore, that travel time in the tile drain itself is not of importance when considering temporal hydrograph parameters.

Besides showing the important influence of local ground slope, the data of *Fig. 2* also serve to illustrate the reduction in time of concentration that might be expected when secondary storms fall on a soil already wetted by previous rainfall. The average of the median t_c values of these secondary storms is 2·17 h. This compares with 3·74 h for the simple storm group, a reduction of 1·57 h. As well as the general fall in t_c values, there is less scatter in the plot of t_c against ground slope (r^2 is 0·56 compared with 0·39 for the simple storm case). This undoubtedly reflects a less complex drainage response to secondary storms. The pattern could perhaps be anticipated given that soil wetness would be more uniform as the secondary burst of rain began to fall than it would be before the first fall of any storm. However, while the effect of ground-slope on drain response is still evident in the case of these secondary rainfalls in complex storms, it is less pronounced (*Fig. 2, top right*). The regression coefficient of the least-squares relationship between ground-slope and time of concentration has a value that is only 57% of that for the simple winter storms. Time of concentration does not fall off as rapidly with increasing local ground slope for these close-following secondary rainfalls. The influence of gradient noted in the case of the simple storms is partially compensated by the greater continuity of pore-water that comes from previous wetting. Water falling on shallower slopes is able to move faster through the plough layer. Because of this, it can be seen (*Fig. 2 top left* and *top right*) that the response of the lateral draining a 3·6% slope is reduced from 6·09 to 3·16 h, while that of the lateral draining a 5·1% slope only changes by 2·09 h.

For the non-winter period (*Fig. 2 bottom left*) it is interesting to note that, even though a wide range of soil moisture deficits prevail at this time of year, the pattern that emerges from the plot of time of concentration against ground slope tends to be broadly similar to that of the simple winter storms. It is during the non-winter period that shrinkage cracks play an important role in routing water into the subsoil (Reid and Parkinson[16]). Even though shallow plough-layer interflow is less significant at this time than it is in winter in transmitting rain quickly into the drains, water can by-pass the topsoil by way of the seasonal cracks and is conducted to the tile drains after moving through the mole channels. But despite the fact that the pattern is broadly similar with t_c reducing as slope increases, absorption of water by the soil matrix succeeds in delaying the arrival of the hydrograph peak at the drain outfall. The average median t_c for the six laterals is 4·69 h in the case of the non-winter group. This compares with 3·74 h for the simple winter storms, a difference of almost 1 h. The faster response during winter, when antecedent water contents are higher, reflects both the smaller pre-storm water storage capacity of the soil and the greater likelihood of continuity of water in the transmission pores at this time of year. The even faster secondary winter hydrograph rises illustrate a further exaggeration of the combined effect of these two factors since the water content of the soil antecedent to these secondary rainfalls is conditioned by the addition of rain only hours before.

3.3. *Ground slope and peak drain discharge*

Fig. 3 illustrates the effect of changes in local ground slope on peak storm discharge from the drains on this topographical convexity. As with time of concentration, peak discharge per unit drain length falls dramatically with increasing slope gradient, at least for the winter period (*Fig. 3 top left*). This inverse effect of ground slope is even more marked in the case of secondary winter rises (*Fig. 3 bottom*). Yet, for the non-winter period there appears to be no correlation between the two variables (*Fig. 3 top right*).

3.4. *Ground slope control of tile drain catchment area*

On level ground, and assuming uniform soil conditions, a tile drain bisects its catchment

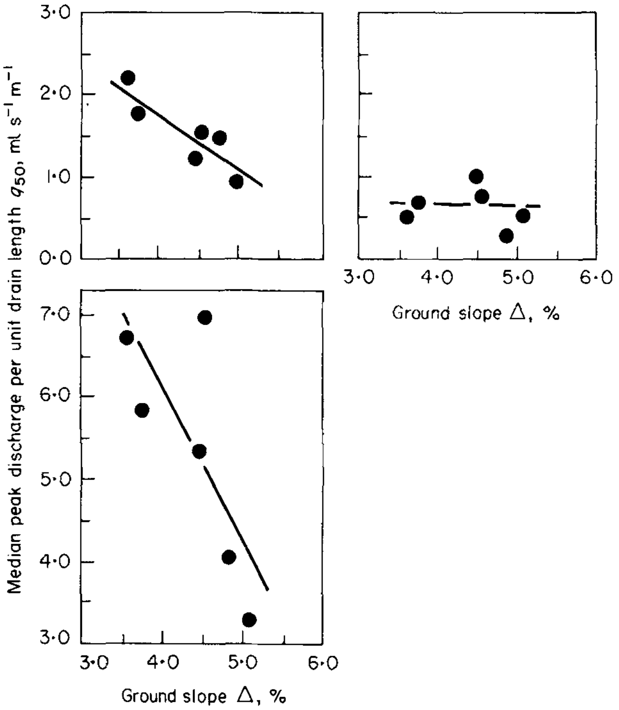

Fig. 3. Relationship between local ground slope (Δ) and median values of drain storm peak discharge per unit drain length (q_{50}). (Top left) simple winter storms, $q_{50}=4{\cdot}44-0{\cdot}67\Delta$, $r=-0{\cdot}864$. (Top right) simple non-winter storms, $q_{50}=0{\cdot}70-0{\cdot}02\Delta$, $r=-0{\cdot}039$. (Bottom left) secondary winter storms, $q_{50}=13{\cdot}34-1{\cdot}82\Delta$, $r=-0{\cdot}711$

and the drainage divide is equidistant between adjacent drains (Childs,[3] Kirkham[21]). If the ground slopes uniformly over an area, total storm drain discharge is the same as for the horizontal case, but the drainage divide shifts upslope (Carlson,[12] Zeigler[13]). These are simple, almost idealized topographical situations. In the case of convex slopes, as here, where gradient increases progressively downslope, the drainage response will be more complex.

Fig. 4 shows the 40 h storm outfall of tile laterals 2 to 6 plotted against equivalent values for tile lateral 1. Lateral 1 has the catchment with the lowest local ground slope (3·6%) and is used here as a yardstick against which to compare the other laterals. The slopes of the least-squares regression lines have been taken to represent the relative efficiency of each tile drain and these have been extracted and plotted against local ground slope in *Fig. 5*. The trend is clear-cut. The 40 h storm outfall of a tile lateral draining a 5·1% slope (L6) is only half that of one draining a 3·6% slope (L1) in this topographical situation and this soil type.

There are several possible explanations for this behaviour. As ground slope increases, the opportunities for surface run-off increase. This might involve water running over the line of a tile lateral without passing down into it. However, this is hardly likely to affect the *general* pattern that has been established during more than four years of observations. During this time, overland flow has been observed on only three occasions. Each of these was a response to exceptional rainfalls, the average intensity of which exceeded 10 mm/h in all three cases. For the majority of drainflow events, rainfall intensity did not exceed infiltration capacity, and overland flow did not occur. Because differences in overland flow at different points on this convex slope cannot be invoked to explain the general variable pattern of drain efficiency, the mechanism must lie below the surface.

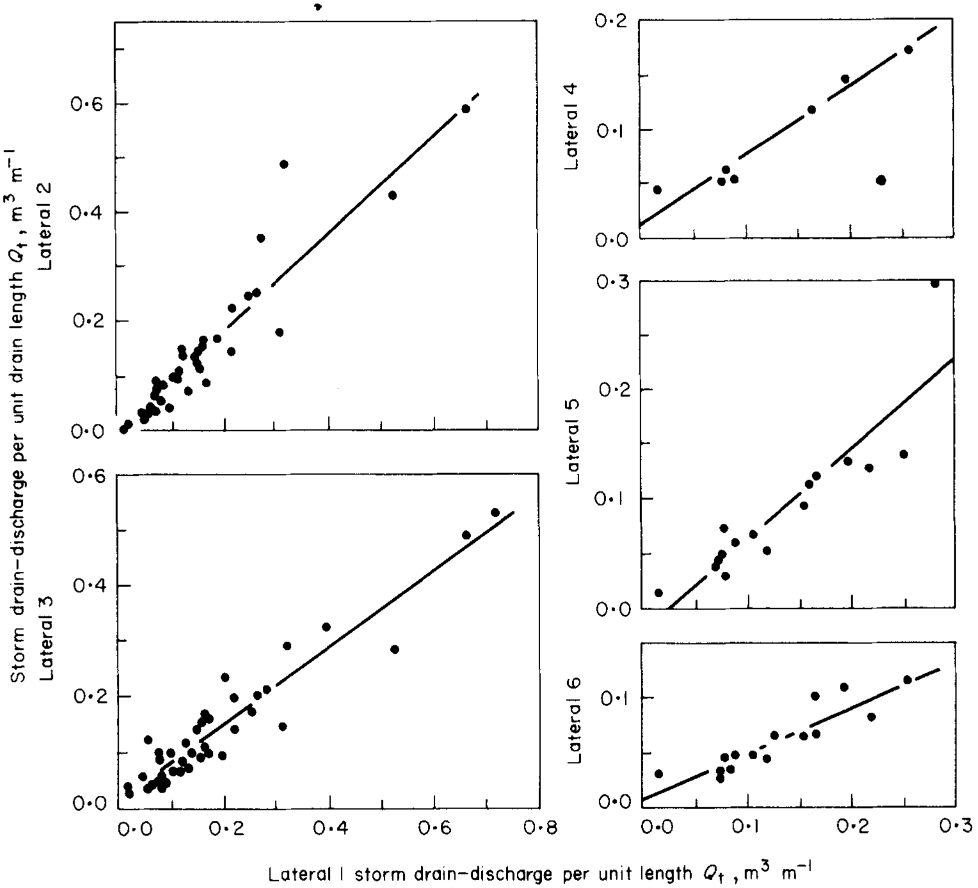

Fig. 4. Storm drainage of tile laterals L2 to L6 plotted against storm drainage of tile lateral L1, for simple winter storms only. Storm drainage is standardized and expressed per unit drain length. (Top left) L2 $Q_t = 0{\cdot}01 + 0{\cdot}91$ *L1* Q_t, $r = 0{\cdot}950$; *(bottom left) L3* $Q_t = 0{\cdot}02 + 0{\cdot}70$ *L1* Q_t, $r = 0{\cdot}950$; *(top right) L4* $Q_t = 0{\cdot}01 + 0{\cdot}65$ *L1* Q_t, $r = 0{\cdot}972$; *(mid right) L5* $Q_t = -0{\cdot}02 + 0{\cdot}84$ *L1* Q_t, $r = 0{\cdot}899$; *(bottom right) L6* $Q_t = 0{\cdot}01 + 0{\cdot}41$ *L1* Q_t, $r = 0{\cdot}901$

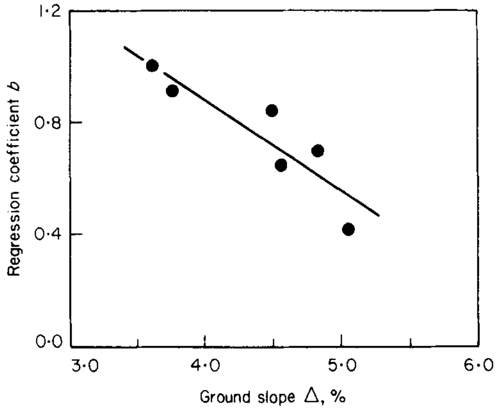

Fig. 5. Tile drain storm drainage relative to that of Lateral 1 expressed in mean terms by the values of the regression coefficient b *of the least-squares curves in* Fig. 4, *where* $y = a + bx$. *In this figure,* $b = 2{\cdot}20 - 0{\cdot}33\Delta$, $r = -0{\cdot}903$

Once water has entered the soil, its direction of flow is also controlled in part by ground slope. Carlson[12] and Zeigler,[13] among others, demonstrate that as slope gradient increases, the drainage divide between tile drains shifts upslope. They envisage an isotropic soil and a free-water surface (a water-table) that marks the top of the saturated zone. This is clearly an inappropriate model for heavy clay soils with their low sub-soil hydraulic conductivities. But it does serve as a basis for conceptualizing an upslope shift in the drainage divide of plough layer interflow (*Fig. 6*). It helps to explain the observed differences in drain performance on this convex slope. The loss of catchment area that results from the closer approach of the drainage divide on the downslope side of a tile drain on steeper ground slopes is not being compensated by an extension of the contributing area on the upslope side of the drain, at least as far as the rapid disposal of water is concerned (*Fig. 6*). This is attributed to a number of factors which include the tortuous nature of the flow-path within the plough layer and the way in which this impedes transmission towards the fissured soil that overlies the tile lateral. This loss of contributing area with increasing ground slope is the reason for the reduction in drain efficiency (*Fig. 5*). It also serves to explain the reduction in peak drain discharge shown in *Fig. 3*. Less water is converging on the laterals that drain the steeper parts of the slope.

The variable efficiency of the drains can be used with caution to determine the actual catchment area that is contributing quick-return flow (i.e. the outfall in 40 h) to an individual tile lateral. Isolated storms must be selected to avoid including the delayed discharge of any preceding storms. Storm drain discharge is then divided by the storm rainfall of the apparent catchment as determined from planimetric maps in which the drainage divides are set arbitrarily equidistant between adjacent drains. This has been done for an isolated simple winter storm (*Fig. 7*). The inverse relationship between ground-slope and drainage outfall (expressed as a percentage of plan area rainfall) corroborates the general pattern established for drainage response to all storms (*Figs 4* and *5*). However, because there is no significant change in soil water storage (i.e. absorption by the soil matrix) during this isolated storm event, and because evaporative losses are negligible at this time of year, the percentage drainage yields are reasonably precise measures of the proportions of the apparent (i.e. plan) catchments contributing to short-term outfall. The primary reason for installing tile-drains is rapid removal of water that would induce conditions

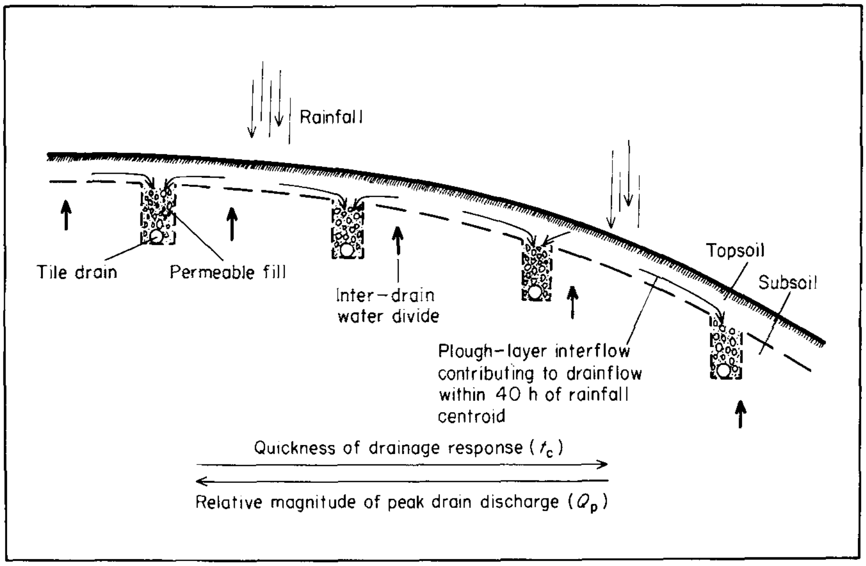

Fig. 6. Schematic representation of changing drain catchment area on a convex slope when the heavy clay soil is fully rewetted and water contents are at their winter mean

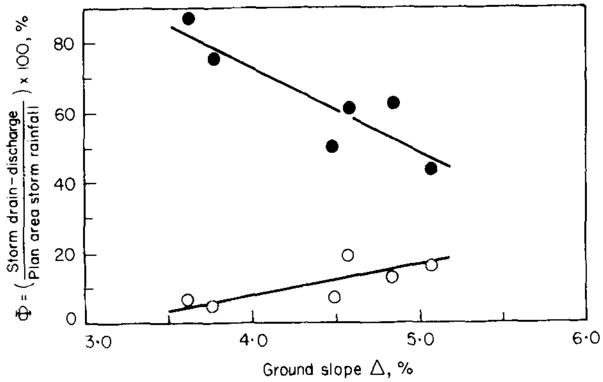

Fig. 7. Percentage of plan catchment area contributing quick-return flow (40 h) drainage as a function of local ground slope. ● *winter storm (13.3.81) with soil moisture deficit zero,* $\Phi = 170{\cdot}08 - 22{\cdot}47\Delta$, $r = -0{\cdot}883$. ○ *non-winter storm (15.11.80) demonstrating the effects of differential water contents, caused by slow diffusive interflow, on the absorption of rainfall and thereby on drainage response at times when soil moisture deficits prevail.* $\Phi = -24{\cdot}71 + 8{\cdot}12\Delta$, $r = 0{\cdot}779$

deleterious to plants. Yet the data of *Fig. 7* indicate that drainage efficiency is more-or-less halved as slope gradient increases from 3·6 to 5·1% on this convex slope. This is because the actual contributing catchment falls from 82 to 45% of the notional plan catchment, a pattern that is shown schematically in *Fig. 6*.

An example of non-winter storms is also given in *Fig. 7* to illustrate seasonal complexity. It shows an opposite, if comparatively weak trend to the winter storm. The reason for this apparent seasonal contradiction lies in the influence of deeper seated and slower interflow on the water content of the soil at progressive downslope positions during a time of year when soil moisture deficits prevail. It was noted in all four years of the study that the tile drains at the foot of the slope would produce a low-flow trickle discharge for several weeks beyond that point at which upslope drains had ceased to run in early summer. This implies a slow downslope diffusion of water by deep interflow and a soil moisture content thereby maintained locally at higher levels. As a result of the higher antecedent moisture content, a lower proportion of non-winter period rainfall is absorbed by the wetter soil matrix at the steeper downslope sites and drain outfall is marginally greater. This non-winter drainflow response cannot be used in the same way as the winter pattern to describe the contributing catchment areas of the drains because of differential absorption by the soil matrix. It is useful, however, as an indication of the way in which water is handled by the soil. It demonstrates the role of slow and deep interflow in redistributing water even in heavy clays.

4. Conclusions

The traditional drainage design for level or uniformly sloping land involves regularly spaced tile laterals, while in areas of undulating topography drain spacing is varied to favour depressions in the landscape. For convex landforms where slope angle increases downslope, it has been shown here that drainage response and drain efficiency are related to local surface gradient. During winter months, when the soil is fully wetted, the lag between rainfall and peak drainflow decreases and the hydrograph is flashier as ground slope increases. But both peak discharge and drainage efficiency expressed as 40 h storm outfall are considerably reduced.

The detailed analysis of drain outfall hydrographs can be an aid used to improve drainage design. Since drain efficiency has been shown to vary with small changes in ground slope, the form of the land must be a factor taken into account when determining optimum drain spacing in different soils on rolling topography. In particular we show that there should be no presumption that clay soils on convex landforms are naturally better drained.

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