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The Grendon Underwood field drainage experiment

by

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Report No 65

March 1980

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THE NATURAL ENVIRONMENT RESEARCH COUNCIL

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1. INTRODUCTION

The extensive area of the British Isles that has been subject to field under-drainage has been recorded by Green (1973, 1976, 1979) and continues to increase. The effect of such field drainage on river flows has been the subject of considerable debate and continuing reassessment. Research to date suggests that field drainage may both increase and decrease river peak flows under different circumstances.

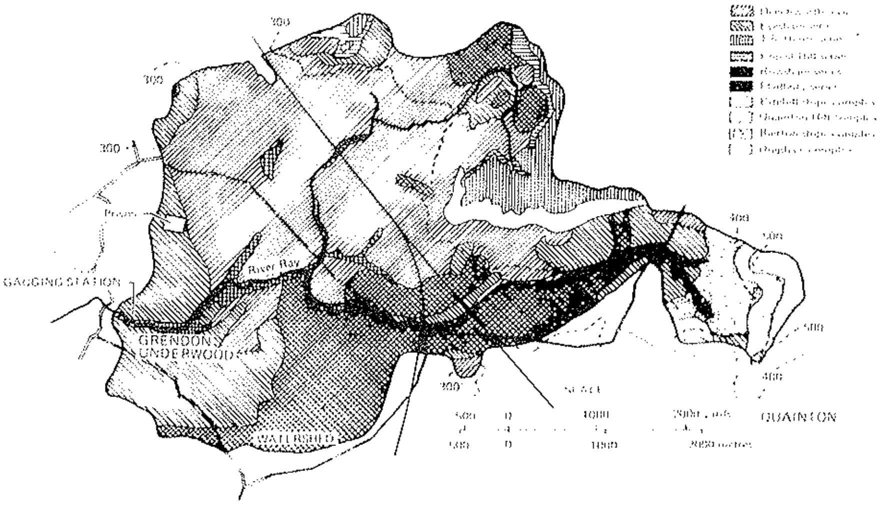
Discharge from The River Ray catchment above Grendon Underwood, near Oxford, England, has been monitored by the Institute of Hydrology since 1963. Since then there has been an increasing area within the catchment that has been drained by mole and tile drainage, and it is expected that this and further future drainage will change the hydrological response of the catchment. The aims of this study are to assess the importance of field drainage on the catchment as a whole. This report includes an analysis of catchment records and the results of a field experiment within the catchment that compares the discharge from drained and undrained plots.

2. THE RIVER RAY CATCHMENT ABOVE GRENDON UNDERWOOD

The headwaters of the River Ray drain an area of 18.5 km^2 upstream from the village of Grendon Underwood (Figure 1). With the exception of Quainton Hill which is an outlier capped with Lower Greensand, the

FIGURE 1

The River Ray experimental catchment



entire catchment is underlain by Jurassic clays, predominantly Ampthill and Oxford Clays, which increase in thickness to the north-west to a maximum depth of 30 m. The hills that form the northern watershed have a thin covering of glacial drift, and there are some head deposits towards the centre of the catchment. However, the southern area appears to be free of surficial deposits resulting in a gradation from heavy stone-free soils developed on pure Oxford Clay in the south to somewhat lighter soils in the north. The more permeable soils and rock of Quainton Hills are sufficient to supply some small springs at the base of the hill that maintain flow in dry weather (Blyth and Rodda, 1973). This catchment has been the subject of both water balance and hydrological modelling studies (Edwards and Rodda, 1970; Nash and Sutcliffe, 1970; Mandeville *et al.*, 1970; Summers, 1977).

A full soil survey of the catchment is shown in Figure 2 from which it is seen that the bulk of the catchment area is underlain by soils of the Denchworth, Evesham and Rowsham series. The descriptions that follow have been adapted from Avery (1959). The Denchworth series (Kay, 1934) consists of decalcified grey soils with tenacious yellow and grey-mottled subsoil horizons, developed for the most part on Oxford clay. The presence of occasional flints and quartzose pebbles, and sporadic sandy inclusions, indicates that the upper part of the profile, perhaps 50 cm, represents a re-worked or solifluxion layer. Typical profiles under pasture consist of a dark-coloured A horizon, which may range in texture from clay loam to clay, 15-25 cm thick and showing rusty mottling along root channels. Below this is a non-calcareous clay subsoil of coarse blocky to prismatic aggregates, mottled reddish-yellow internally, merging into grey and yellow-brown mottled calcareous clay at depths of 45-100 cm.

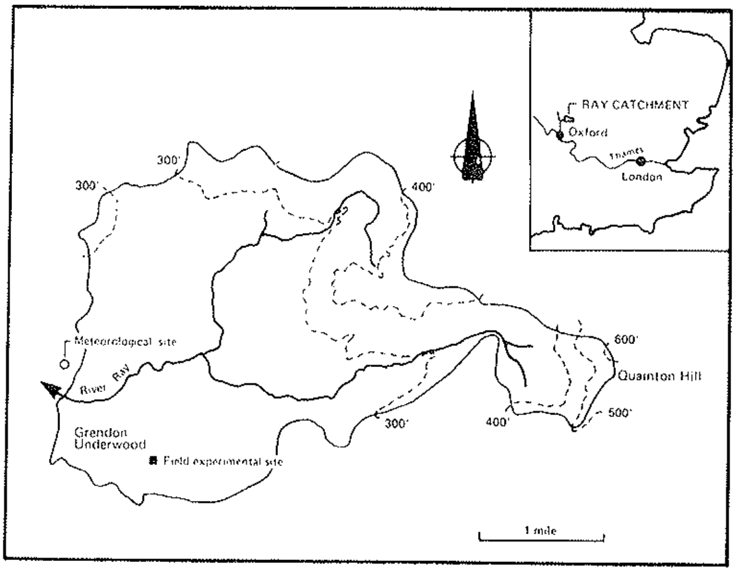


FIGURE 2 Soil map of the River Ray experimental catchment

The Evesham series (Avery, 1955) are tenacious clay soils formed on the Oxford clay and are distinguished from the Denchworth series by the morphology of the subsoil which is less prominently mottled and is frequently calcareous throughout. There is usually a gradation between the two series types with no clear boundary between them. As with the Denchworth series, a few stones are commonly present, and sporadic patches of gravelly or sandy clay may be found in the subsoil, indicating contamination with small amounts of drift. This condition is particularly prevalent to the east of Grendon Underwood where the soils grade indefinitely into those of the Rowsham series.

The Rowsham series is developed where the Jurassic clays are covered by at least 40 cm of drift containing appreciable amounts of sand and stone derived either from glacial deposits or from the Cretaceous outliers. Compared with the Denchworth and Evesham series, the soils are distinctly friable and are typically clay loams though loams and clays are also found. The base of the drift is commonly marked by a coarser textured, ochreous, gravelly layer of irregular thickness, though this is rarely sufficiently thick or continuous to afford effective under-drainage.

Further details of the other soil series are available in Avery (1959). From studies of neutron probe soil moisture measurements carried out in 1965-1972 by the Institute of Hydrology it would appear that all the clay soils of the catchment are hydrologically quite similar, maintaining high water tables and occasional surface saturation on areas of low slope during the winter months. During summer the soils exhibit considerable shrinkage on drying and dessication cracking has been observed to depths of at least 50 cm (1978).

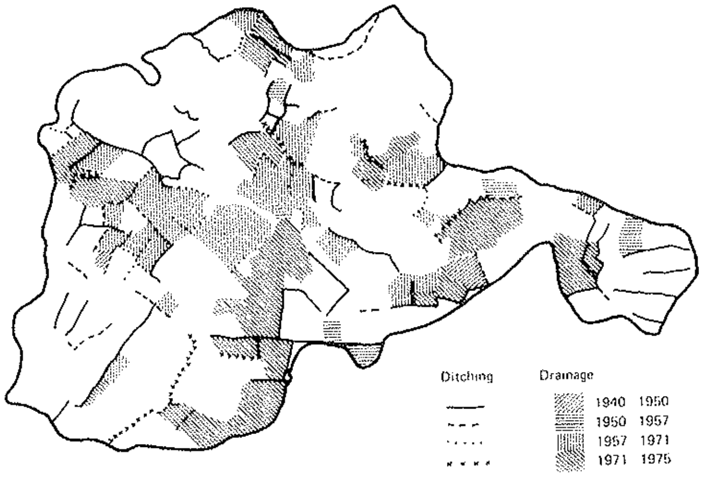


FIGURE 3 Ditching and drainage in the River Ray experimental catchment

The major land use in the catchment is permanent pasture (some 70%), with smaller areas of arable land and mixed deciduous woodland. The heavy nature of the clay soils in the River Ray catchment, leading to a tendency to waterlogging in the winter, provides a good case for the initiation of field drainage schemes. The extent of field drainage and ditching operations in the catchment is shown in Figure 3 which was compiled by F.H.W. Green from information provided by the Field Drainage Experimental Unit of the Ministry of Agriculture. In fact further areas have been drained in every year since 1975. Thus, if the drainage of clay land is to have an effect on stream flow, the considerable under-drained area of the River Ray catchment should demonstrate that effect.

3. THE EFFECTS OF FIELD DRAINAGE ON RIVER FLOWS

> 'The Reverend Clutterbuck, having lived near the Thames for 30 years said that the flood water in it came from the areas occupied by the outcrops of the Oxford, Kimmeridge and Gault clays respectively. Near Abingdon, the floods used to reach their highest levels within 72 hours, but the under-drainage of the past 20-30 years had reduced this interval to 36 hours. He did not state whether the peak was as high as formerly'.

(Nicholson, 1953; reviewing the discussion of a paper on field drainage given by J Bailey Denton at the Institution of Civil Engineers in 1861).

The work of J Bailey Denton represented some of the earlier research on the effects of field drainage on river flow, and concluded that field drainage would increase the volume and decrease the response time of flow in rivers, a conclusion reinforced by the observations and reasoning of those contributing to the discussion. This view continues to be advocated today (Ward, 1975, p 274), and is primarily based on the assumption that the provision of drains provides a rapid and shorter route by which water may reach a stream.

However, while this is the prime consideration in the drainage of impermeable (such as urban) areas, there are other factors affecting the response of drained agricultural land. In particular, if drains have the effect of preferentially lowering the water table between storms, there may be additional storage capacity available that must be satisfied before significant amounts of water are transmitted by the drains to a stream channel. By this argument, drainage may <u>decrease</u> peak flows, although higher recession flows between storms may result in higher overall yields. Nicholson (1953) concludes:-

> 'In short, it is possible that field under-drainage everywhere may have the effect of lessening the peak flow of runoff and of minimising flood risk. When land is under-drained and waterlogged, whether it is permeable or impermeable matters not; the only runoff is superficial and must be of the flush type.'

Yet, if there is a likelihood that drainage may not preclude the occurrence of surface or quick response flow, it may still be argued that, in this flood flow case, the higher density of drains may lead to higher peak stream flows. It is likely, then, that the effect of drainage on streamflow will be extremely complex, depending on the type of drain, whether surface or subsurface, the spacing of the drains, the type of soil, the intensity and duration of rainfall and the antecedent moisture conditions. Wisler and Brater (1949) suggest that sites within a catchment may also be important.

> 'In the lower portions of a drainage basin, speeding up the runoff process is likely to decrease flood flow, whereas slowing down the process may increase the flood peak. In the upper reaches, the effects may be just the opposite.'

(Wisler and Brater, 1949, p 61).

Research work by the Field Drainage Experimental Unit of the Ministry of Agriculture has clarified some of the factors involved. Trafford (1973) concludes that drainage may both increase and decrease river flows depending on the particular circumstances of the case in question. For clay soils, which are the immediate interest here, this was confirmed by the experimental and modelling work reported by Pycroft and Massey (1975). Rycroft and Massey review the results of several field studies of the effects of field drainage and suggest that drainage distributes flow more evenly than that from an undrained area. With respect to flood flows they conclude that:

1. There is no evidence to suggest that under-drainage increases flooding.
2. Mole drainage reduces the peak outflow rates from a catchment for heavy storms which are liable to give rise to flooding.
3. Mole drainage maintains water table levels usually at 50 cm depth, the water table rises during storms but is quickly lowered after rainfall thus creating storage space for further rainfall.
4. Undrained clay catchments have limited storage which is filled up quickly during storms. Further rainfall then results in runoff.
5. An undrained waterlogged clay catchment remains wet for a considerable time after rainfall thus providing no buffer against further rainfall.' (Rycroft and Massey, 1975, p 11).

This neatly summarises the present state of knowledge regarding the effects of drainage on river flood flows. It is the purpose of this study to test these conclusions for the particular case of the clay-land drainage in the River Ray catchment.

4. THE EFFECTS OF FIELD DRAINAGE - RIVER RAY CATCHMENT RECORDS

Hourly records of average catchment rainfall and discharge from the River Ray catchment were available for the period October 1963 to September, 1977. This large amount of data was stored on magnetic tape at the Institute so that an initial computerised analysis of the data was possible. An analysis program was written to calculate total monthly rainfalls and discharges; and to identify hours for which discharges were greater than 0.5 mm/hr (2.58 $m^3 s^{-1}$); the time and magnitude of the peak discharge within each such period; rainstorms for which there was a continuous period of rain totalling more than 10 mm; and the time and magnitude of the peak rainfall intensity within each such period. The output from this program was used as a guide in selecting significant storms to examine possible effects of field drainage on the flow of the Ray.

Looking first at monthly totals of rainfall and discharge it was expected that catchment response in terms of the monthly volume of discharge delivered to the catchment outlet would be very dependent on both rainfall and evapotranspiration within the month, and the effects of antecedent soil moisture conditions. The effects of evapotranspiration are obviously greatest in the summer months and this will generally also lead to more highly variable antecedent conditions for the summer months. However, variations in rainfall amounts may have an even more important effect on antecedent conditions throughout the year. The influence of antecedent conditions will only be minimised when the catchment has wetted up in the winter. Further analysis has therefore been restricted to the winter months (October to March) to facilitate the identification of the influence of field drainage alone.

Figure 4 shows double mass curves of cumulative discharge plotted against cumulative rainfall for each of the 6 winter months over the 14 winter periods available. The months have been plotted separately to isolate further possible seasonal effects. November is seen to be the wettest month on average, and March the driest of the winter months. The slope of a straight line drawn between the end points of each line represents an average delivery ratio (discharge/rainfall by volume) for each month. It is seen that most of the points plot above this line suggesting that the delivery ratio is tending to decrease over time. This could be due both to the effects of field drainage and year to year variations in rainfall. (Note the curve for October in particular where it would appear that a wet spell (1965-1968) separates two dry

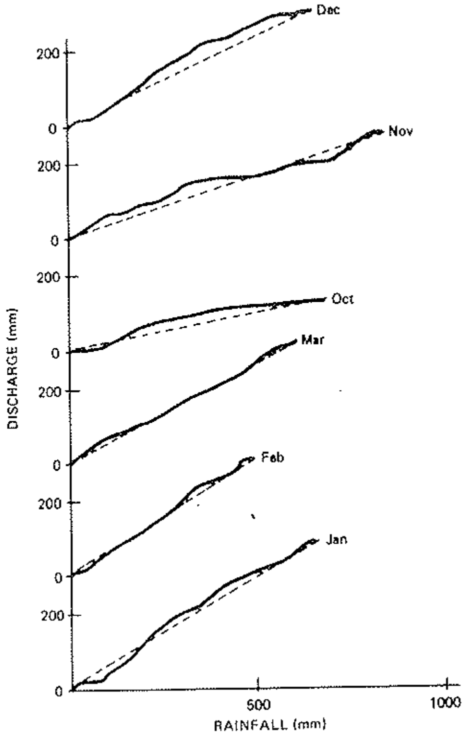


FIGURE 4

Cumulative rainfall plotted against cumulative discharge for the River Ray catchment 1963-1977 winter months

spells.) The influence of annual variations in rainfall is confirmed by analysis of the delivery ratios for individual years. Figure 5 shows these ratios and a 5 year running mean for the months of October and February which have the lowest and highest average delivery ratios respectively. Both months show a tendency for the delivery ratio to decline after an initial rise, but it is impossible to determine how much of this change is due to natural fluctuations in rainfall and how much due to the effects of field drainage. Plotting delivery ratio against monthly rainfall for the two months shows an extremely variable relationship (Figure 6a) but the variance may be reduced by replacing monthly rainfall by total rainfall in that month and the previous 5 months, (Figure 6b) which is a crude summary index of both antecedent conditions and rainfall within the month concerned. This would suggest that antecedent conditions are important even in February when it might be expected that the catchment has, in most years, thoroughly wetted up.

Thus, it appears that, in respect of monthly discharge volumes or delivery ratios, the effects of field drainage are relatively minor compared with natural fluctuations in the inputs and processes of catchment response and are certainly too small to be distinguished with the simple screening techniques employed so far. Far more sensitive techniques would be required, especially since, although changes in field drainage are progressive, any detectable effects of field drainage may not bear a simple relationship to the area drained.

Turning to individual winter storms, a sample of 38 storms resulting in a peak discharge of greater than 0.5 mm/hr was available, an average of 2.7 storms per year. For each storm a peak hourly delivery ratio,

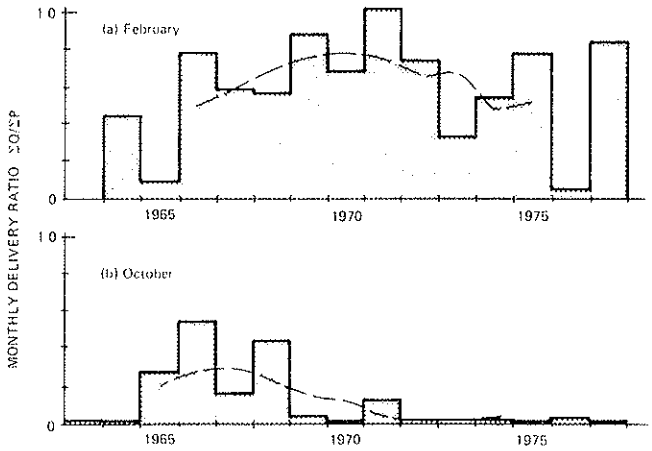


FIGURE 5 Monthly delivery ratios for February and October, 1963-1977, with 5-year moving average (dotted line)

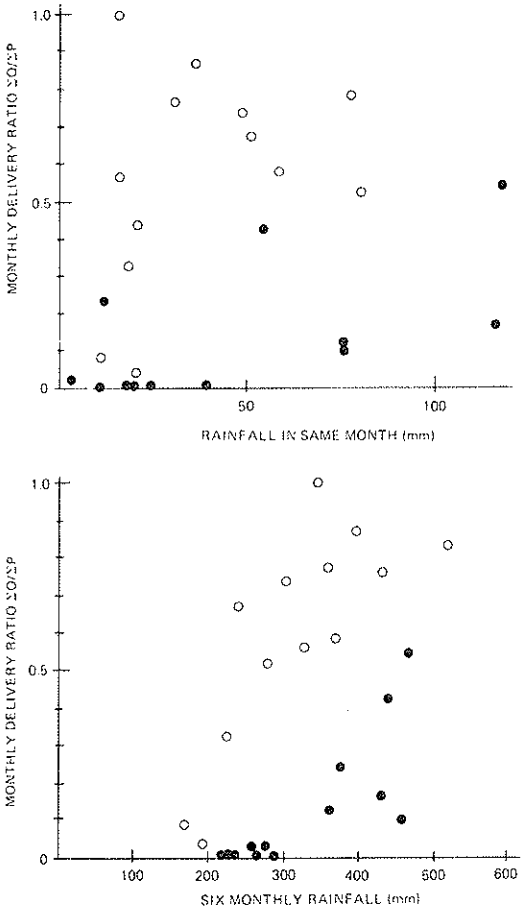


FIGURE 6

a: Monthly delivery ratio plotted against rainfall in same month, February (circles) and October (crosses) 1963-1977

b: Monthly delivery ratio plotted against total rainfall in same month and preceding 5 months. February (circles) and October (crosses) 1963-77

DRP, defined by peak discharge/peak rainfall intensity (both in mm/hr) and a peak lag time, TP, defined by the time difference between peak rainfall intensity and peak discharge, were calculated. These, together with peak discharge, QP, are plotted against time in Figure 7. It is obviously extremely difficult to account for the factors influencing the observed changes, of which field drainage is only one. A simple linear regression analysis of the three variables against time results in the equations:

$$
\begin{array}{rcll}
DRP & = & 0.2089 + 0.000015\ T & r = 0.215 \\
TP & = & 9.004 - 0.00018\ T\ \text{hr} & r = 0.12 \\
QP & = & 0.8247 + 0.000030\ T\ \text{mm/hr} & r = 0.141
\end{array}
$$

where T is time measured in days from 1.1.63. The slopes of the regression lines suggest that peak discharge and peak delivery ratio may be increasing slightly over time while the time to peak may be decreasing. However, none of the correlation coefficients or slope coefficients are statistically significant. A multiple regression analysis including area under-drained as an independent variable was not possible due to lack of detailed information on specific drainage projects. However it seems that the evidence of catchment records does not show any major effects of field drainage in the River Ray catchment. Effects on overall runoff volumes cannot be distinguished in the face of year to year variability of rainfall and other factors affecting antecedent conditions. Any effects on peak discharges, peak delivery ratios and time to peak are slight and not statistically significant.

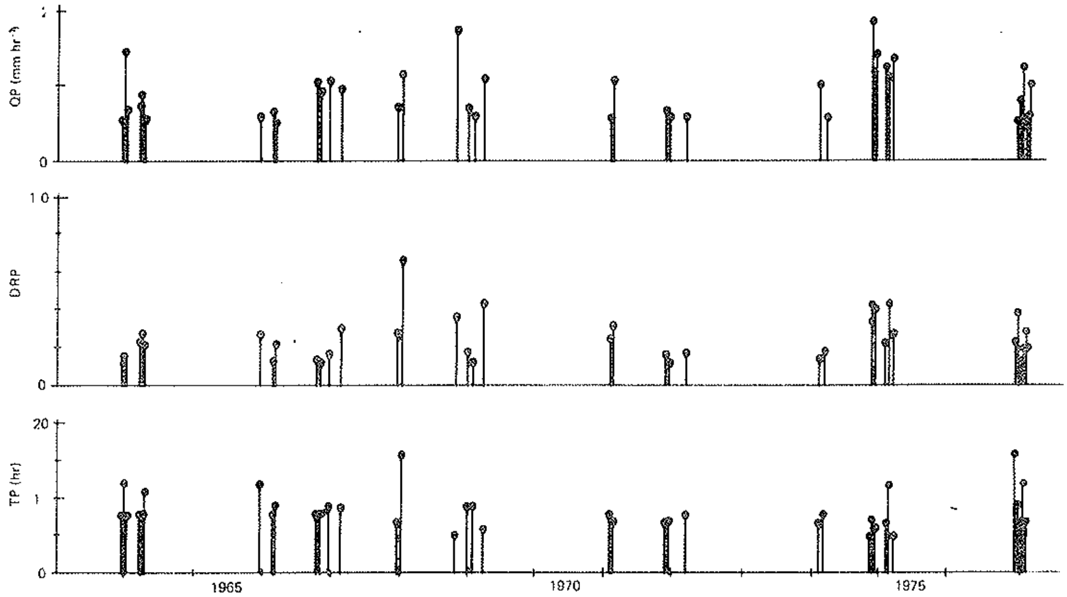


FIGURE 7 River Ray peak discharges, peak delivery ratios and time to peak for winter storms with peak of greater than 0.5 mm hr^{-1}

5. THE EFFECTS OF FIELD DRAINAGE - A PLOT EXPERIMENT

The field drainage experiment at Grendon Underwood was set up to gather information both on the differences in hydrological response between drained and undrained areas for the specific conditions of the Ray catchment, and on the hydrological processes that are significant on drained and undrained areas with a view to consequently modelling those processes correctly. The eventual site chosen for the plot experiment is close to Grendon Underwood village (Figure 1) on a soil classified as Evesham series by Avery (1959). The full site layout and instrumentation plan is shown in Figure 8. The land was previously undrained and the boundary tile drains, flow collecting drains and mole drains on the drained plot were installed specifically for the experiment. All the tile drains were led to an existing ditch where the discharge in the flow collecting tile drains was measured in weir boxes, constructed with a thin plate V-notch weir and equipped with a 1:1 stage recorder with weekly chart (Figure 9). The site is developed on marked ridge and furrow topography orthogonal to the ditch that predates the enclosure of the land in the late 18th century. Adjacent to the ditch, a long period of ditch clearance has resulted in a slight back slope away from the ditch in the ends of the furrows. At the beginning of

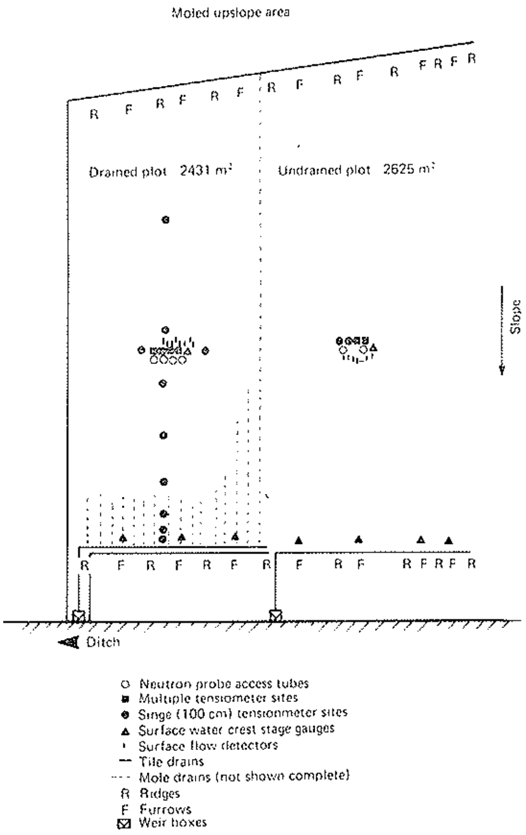


FIGURE 8

Plan and instrumentation of the Grendon Underwood field drainage experimental site

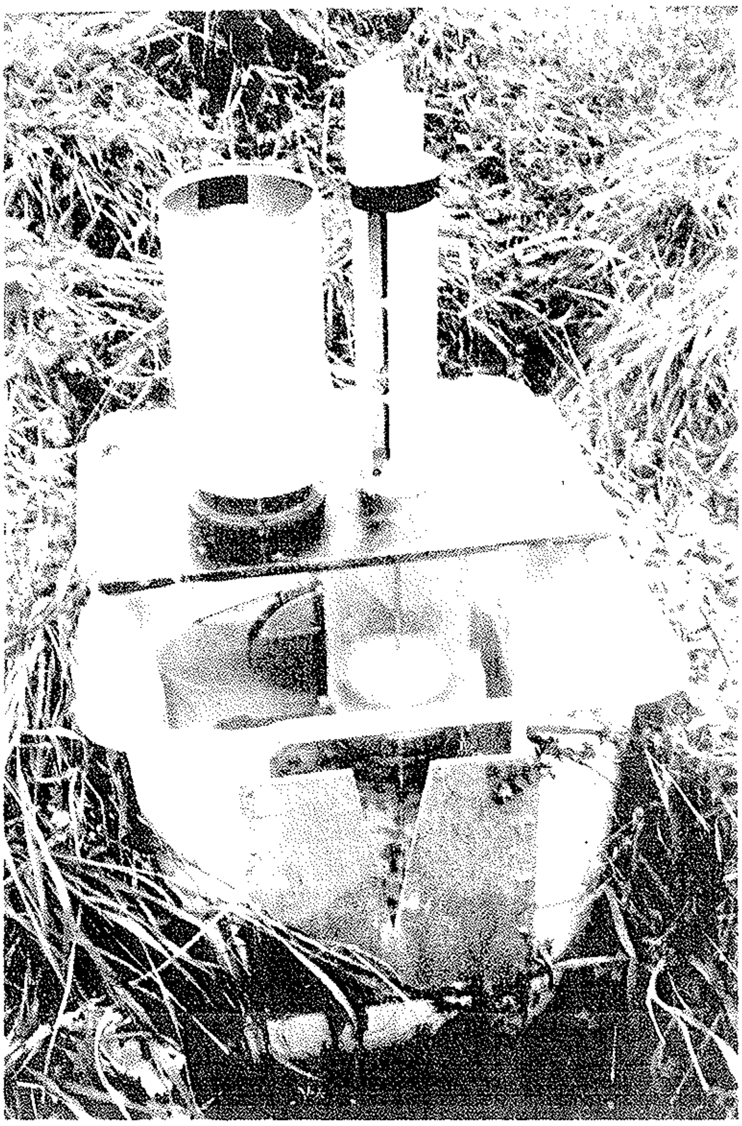


FIGURE 9

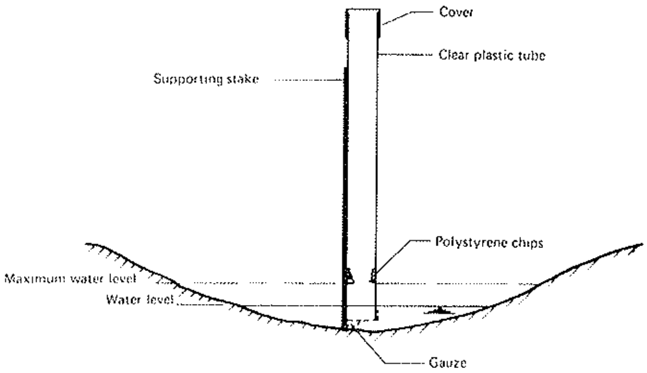
V-notch weir box used for discharge measurements with 1:1 stage recorder and cover removed

the experiment it was therefore decided to instal a surface flow collector (a shallow tile drain at about 30 cm depth and backfilled with gravel) to provide a lower boundary to the drained plot. Flow from this drain was not measured. On the undrained plot, all the surface flow and subsurface flow in the root zone was collected by a single similar shallow tile drain led into one of the weir boxes. Thus any contribution of deep subsurface flow from the undrained plot to the flow in the ditch was not measured. On the drained plot the mole drains drawn at a depth of ∿45 cm were led to a tile drain (at ∿90 cm) backfilled with the existing soil. This tile drain was expected to collect all surface and subsurface contribution from the drainage plot upslope. This flow was measured in the second weir box.

The drainage practice adopted on the drained plot was representative of that commonly employed in the area and was carried out by a contractor used to working in the area. The overall pattern of drains employed in bounding and collecting the flow from the plots assumes that the subsurface matrix flow contribution to flow in the ditch is minimal and may be safely neglected. This is a reasonable assumption under winter conditions once the water table rises above the level of the lowest tile drains, and once cracks in the clay subsoil have closed up.

The investigation of hydrological processes within the two plots has been based on tensiometer measurements, neutron probe soil moisture measurements and point flow collectors and crest stage gauges for measuring the occurrence of surface flow. The layout of this instrumentation is shown in Figure 8 and details of the point surface flow collectors and crest stage gauges are given in Figure 10.

(a) Simple crest stage gauge



(b) Surface flow indicator

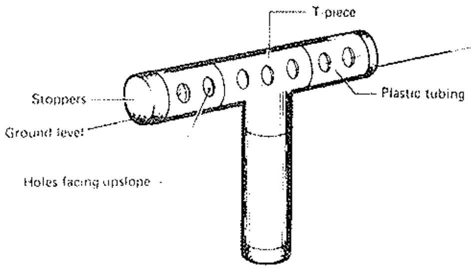


FIGURE 10

a: Simple crest stage gauge

b: Surface flow indicator (otherwise known as crest saturation tubes)

The tensiometers were located in essentially three groups; one consisting of 4 profiles on one ridge to furrow slope central to the drained site at depths of 100, 50, 25, 15 and 5 cm; one on a similar slope central to the undrained site (but with tensiometers at only 100 and 15 cm depths); and one group of 100 cm tensiometers in a profile running parallel to the mole drains on the drained site. The tensiometers at 100 cm depth were used in place of piezometers to indicate the depth of the water table. Tensiometers were used because of the low conducitivity of the clay soil which would result in a very slow response of the more usual open tube piezometers. The tensiometers require only a very small water flow across the tensiometer cup to indicate a change in water pressure, which was measured using mercury manometers. The Field Drainage Experimental Unit has tackled the same problem by designing a narrow (10 mm) 'rapid response' well (Harris 1977).

The instrumentation was completed by four soil thermometers located at a depth of 30 cm close to the tensiometers on the drained ridge site, the drained furrow, the undrained ridge and the undrained furrow. This depth was chosen to reduce any effects of phase differences in diurnal temperature changes between the sites when it was only possible to take temperature readings once a week.

6. RESULTS OF THE PLOT EXPERIMENT; 1977 TO 1979

Weekly measurements were made at the plot experiment site throughout the month of October to April 1977/78 and 1978/79, with some more intensive measurement periods within those seasons, and monthly measurements of soil moisture at the site during the summer of 1978. Instrumentation difficulties proved to be greater than had been foreseen, particularly due to the effects of heavy frosts experienced at the site. The neutron probe moisture measurements were not, however, restricted by frost and measurements were made throughout the study period.

Some of the results are shown in Figure 11. Figure 11a shows the seasonal changes in moisture profile at the drained ridge site while

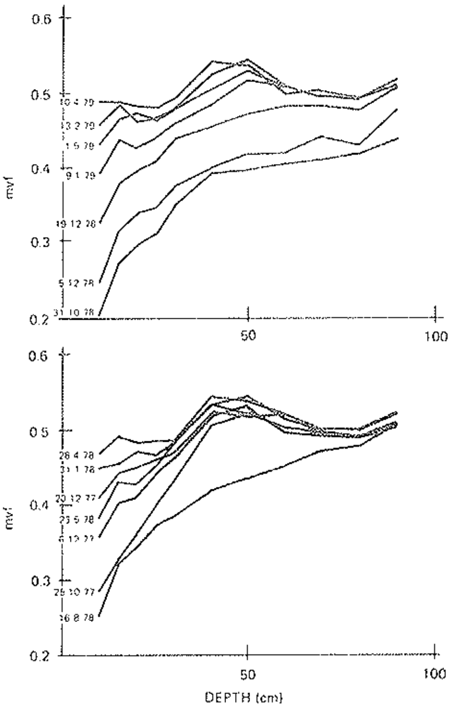


FIGURE 11a

Soil moisture profiles measured by neutron probe for the drained ridge site

Figure 11b compares the ridge and furrow sites on the two plots for specific days. Figure 11c shows the changes in total moisture content at these four sites. It is clear that the ridge sites are always drier than the furrow sites and that the drained sites tend to be drier than the undrained. These differences are greatest in the top 30 cm of soil, the subsoil tending towards constant (saturated) moisture content throughout the winter. This pattern was reinforced at the two intermediate sites on the drained plot where there was always an increase in moisture content from ridge to furrow in the topsoil, but not in the subsoil where site 3 tended towards a lower saturated water content than sites 2 and 4 (Figure 11d).

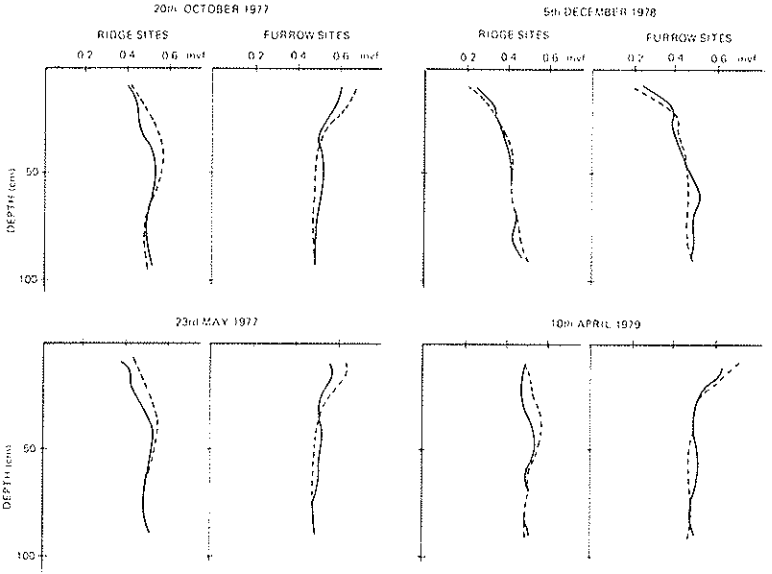


FIGURE 11b

Comparison of drained (solid line) and undrained (broken line) ridge and furrow site moisture profiles for four specific days

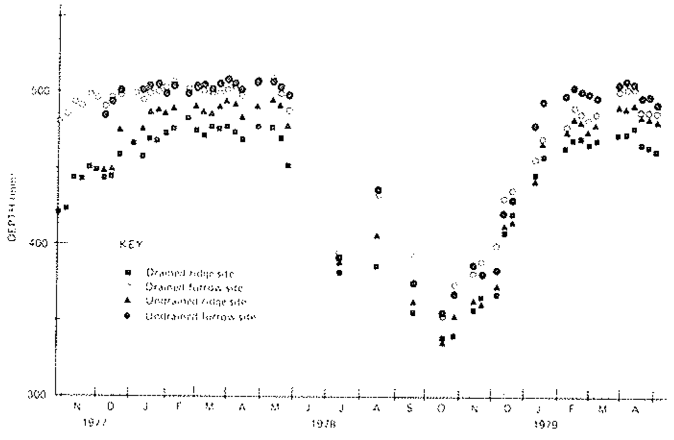


FIGURE 11c

Measured changes in total moisture content in top 95 cm of soil

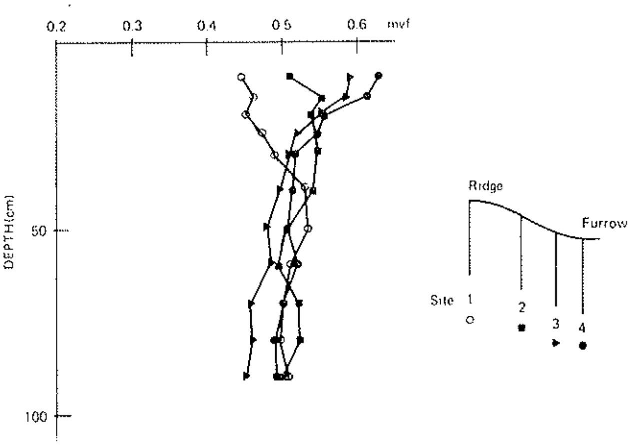


FIGURE 11d Comparison of soil moisture profiles at all four sites on the drained plot, 24.1.78

The soil moisture tension measurements suffered particularly from frosts which caused air bubbles to appear in the manometer system, breaks in the mercury columns or cracked tensiometer tubes. A test carried out at the beginning of December 1977 showed that a 2-3 day period was required after flushing air out of the manometer system before equilibrium tensions were reached in the lowest tensiometers in the clay subsoil (Figure 12). This is indicative of a very low hydraulic conductivity for the clay at this depth. During 1977/78 the tensiometers were not well protected from frost, so a 2-day frost-free period was required prior to a storm before measurements of tension changes

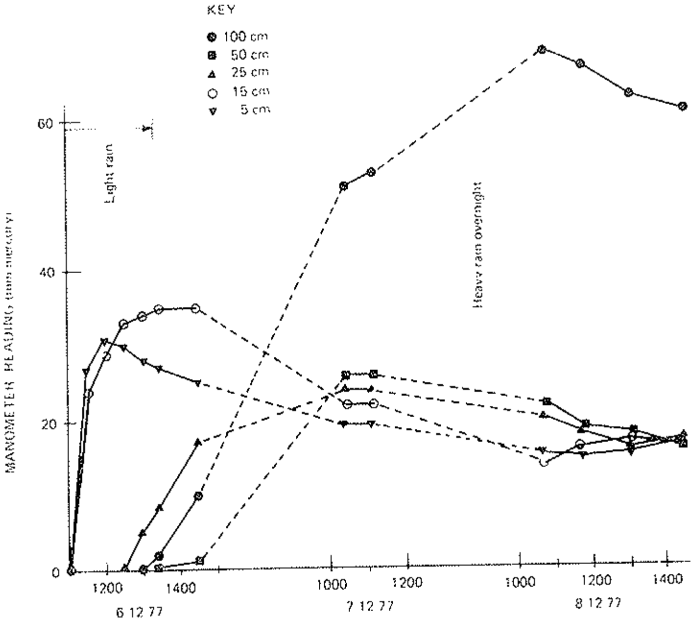


FIGURE 12

Recovery of drained ridge site tensiometers after purging could begin. Some daily measurements were obtained when the farmer, Mr John George, was working nearby but the intention to be on-site to obtain tension measurements over at least one storm was not achieved, several attempts being abortive due to prior frosts. Attempts were made to insulate the tensiometers during 1978/79 using closed cell foam together with protective boxes for the manometer boards, but this was only partially successful.

However, several isolated sets of satisfactory measurements were obtained and these were sufficient to give an indication of changes in the position of the apparent water table over the winter on the drained site (Figure 13). The position of the water table has been interpreted from the nearest positive tensiometer reading and the position of the mole drains. Closer examination of the patterns of hydraulic head of the individual sets of readings reveals that the patterns of flow within this vertical section between ridge and furrow may be complex, the measurements suggesting considerable vertical hydraulic gradients beneath the water table. Such gradients may be more apparent than hydrologically significant, perhaps resulting from the measurement and sampling problems of using tensiometers in soils of very low conductivity.

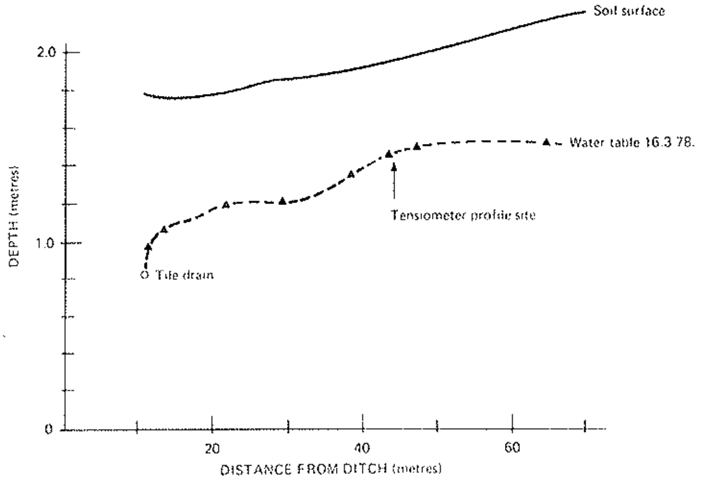


FIGURE 13

Estimated positions of the water table at the drained ridge and furrow site

The tensiometers on the undrained site, and parallel to the mole drains on the drained site, were installed later in the winter and few readings were available. Those that were obtained demonstrate that the tile drain on the drained site does have a significant effect on the water table levels within the clay subsoil (Figure 14).

In fact, the pattern of surface saturation when the water table is at, or above, the soil surface proved to be significantly different between the two sites. This is clearly shown in aerial photographs taken of the site on 7 March 1978. In a broad view of the site, taken with a red filter (Figure 15), areas of surface saturation show as dark tones and reveal the nature of the ridge and furrow topography. A visible light photograph (Figure 16) shows standing water at the downslope end of the furrows, and darker saturated furrow areas elsewhere. The drained site,

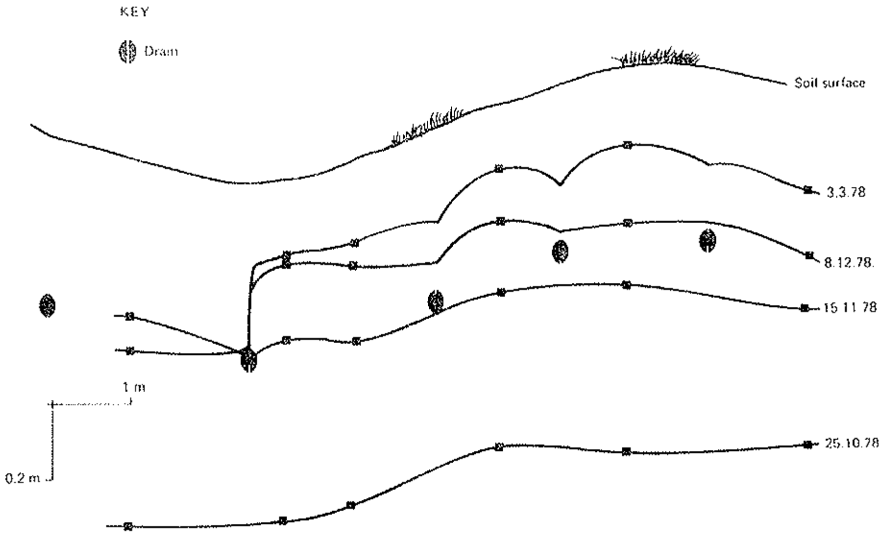


FIGURE 14 Position of water table orthogonal to the tile drain, drained plot, 16.3.78

and the mole drained area upslope of the boundary tile drain is everywhere unsaturated at the surface. This difference is confirmed over a longer period by crest stage gauge measurements (Figure 17a) and surface water collectors (Figure 17b). Trace amounts of water collected in the flow collectors have been ignored in compiling Figure 17b as most probably due to rainsplash. No surface flow was observed on the drained site while in the field, and was never sufficient to cause any measurable rise at the crest stage gauge in the furrow.

Measurements of discharge from the drained and undrained plots suffered from two problems. The first was freezing conditions, with both weir boxes freezing over at times during both winters. The incidence of freezing was greater at the outflow from the undrained site, probably due to the origin of much of this outflow as direct surface runoff. The second problem was limited to the drained site where measurements during the winter of 1977/78 were affected by water levels in the ditch rising above the V-notch of the weir box during high flows. A crest stage gauge was installed in the ditch close to the weir box to check the maximum water level in the ditch, and demonstrated that this effect was not always readily apparent in the recorded stage hydrographs. This problem meant that many of the hydrographs resulting in the highest peak flows during this period could not be used in the analysis. During the summer of 1978 the ditch was regraded by the Thames Water Authority and this problem was eliminated for the following winter which was, however, relatively dry by comparison.

Gaps in weirbox stage records from the two sites precluded the calculation of overall water balances for the two plots. However, such calculations could be made for periods starting and ending at times of similar discharges for which soil moisture data were also available. The results for three such periods are shown in Table 1. Rainfall data were taken from the nearby Grendon Underwood meteorological site (see Figure 1), and the evaporation data were estimates of actual evapotranspiration for a grass surface as calculated by the Meteorological

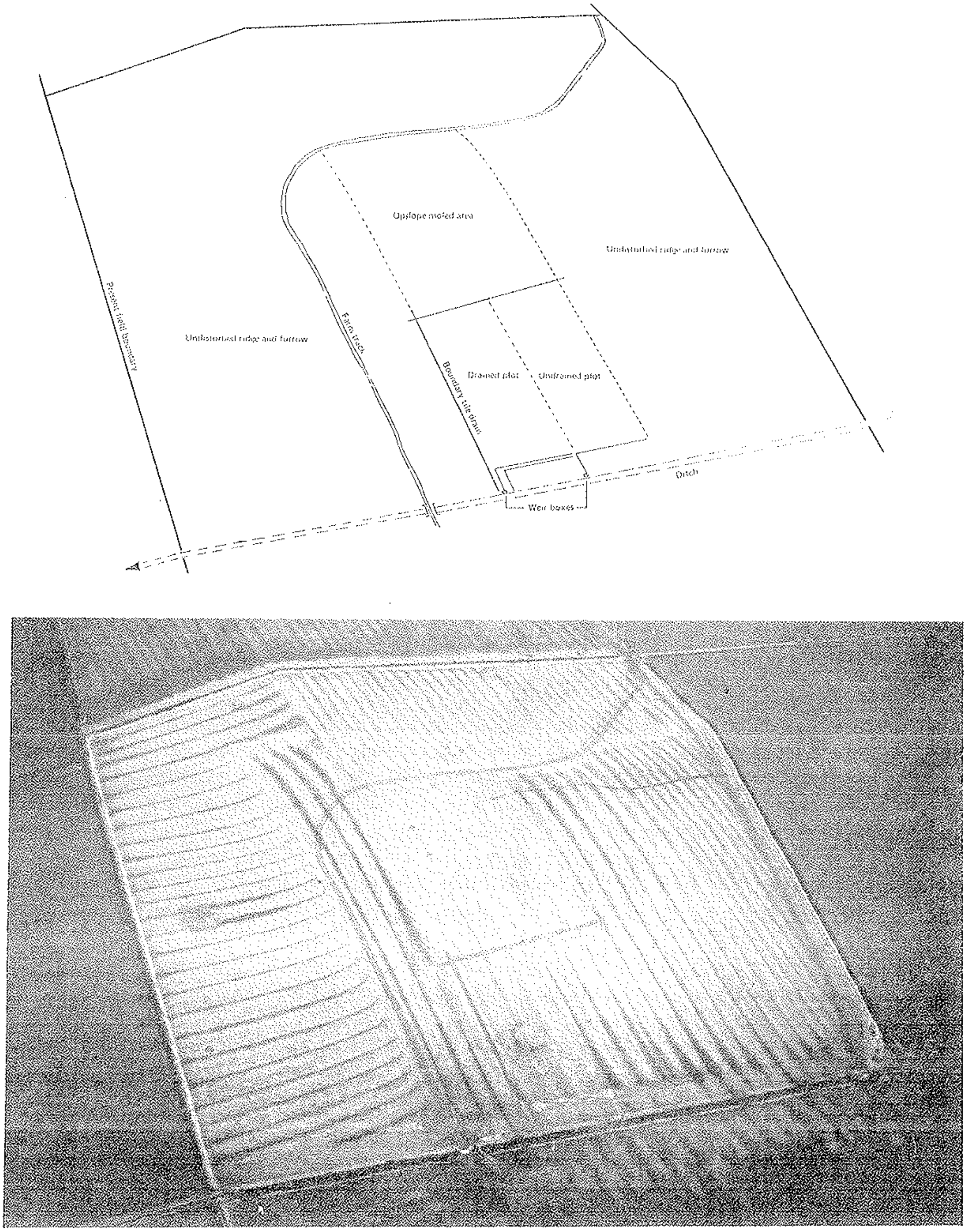


FIGURE 15 Red filtered aerial photograph of Grendon Underwood field drainage experimental site

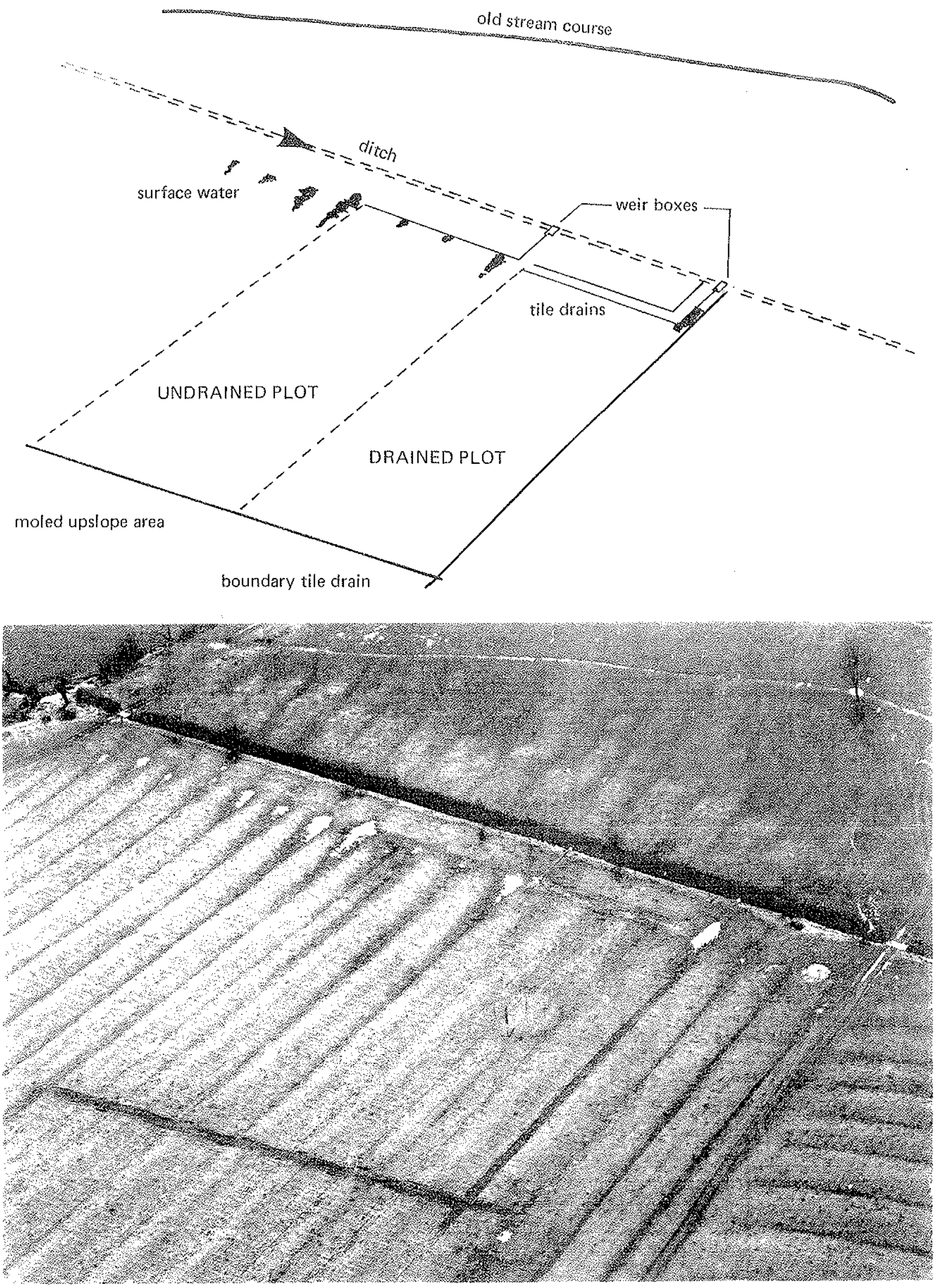


FIGURE 16 Visible light aerial photograph of Grendon Underwood field drainage experimental site

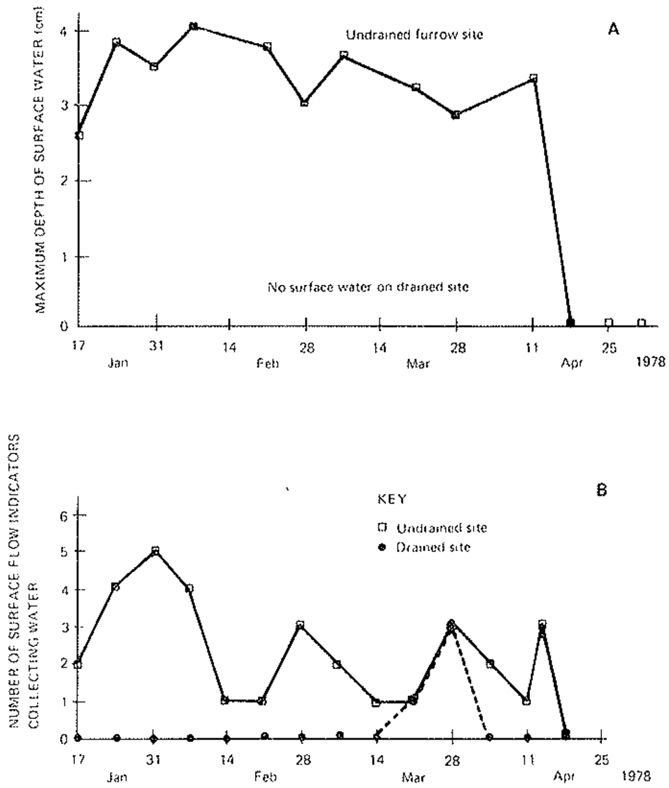


FIGURE 17

a: Results of crest gauge measurements

b: Results of surface flow collector measurements

Office MORECS service in the absence of validated data from Grendon Underwood itself. The discharge from the two plots were calculated from the weirbox stage records using a standard V-notch weir formula (British Standards, 1964) which was checked *in situ* at low flows (Figure 18). From the limited evidence of Table 1, and given that all the components of the water balance are subject to unknown error, the errors in the water balance equation appear to increase with estimated evapotranspiration and were smallest when this term is low and the plots are close to saturation. This allows some degree of belief in the assumption that under such conditions boundary errors were small, and the plot discharges were representative of the hydrological response of the plots. Certainly, under such conditions, a significant proportion of the incident rainfall was measured as discharge from the plots, with the drained plot yielding more flow than the undrained.

The similar size of the two plots allows a comparison of the recorded hydrographs in their original form. A selection of stage hydrographs, unaffected by frost or ditch water levels, are shown in Figure 19 for the winter of 1977/78 and Figure 20 for 1978/79, with peak discharges also given in each case. A comparison of the hydrographs shows that the drained plot tends to be slower to respond to rainfall but that the timing and quantities of peak discharge are similar, the drained site discharge being somewhat lower in most cases.

TABLE 1: RESULTS OF WATER BALANCE CALCULATIONS FOR DRAINED AND UNDRAINED PLOTS

	Drained	Undrained
28.2.78 - 7.3.78		
Rainfall (mm)	11.5	11.5
Discharge (mm)	9.7	8.1
Evaporation (mm)	3.0	3.0
Change in soil moisture (mm)	- 2.2	- 0.2
Balance (mm)	1.0	0.6
5.12.78 - 12.12.78		
Rainfall (mm)	48.3	48.3
Discharge (mm)	7.1	5.5
Evaporation (mm)	8.0	8.0
Change in soil moisture (mm)	36.9	38.1
Balance (mm)	- 3.7	- 3.3
10.4.79 - 17.4.79		
Rainfall (mm)	9.7	9.7
Discharge (mm)	7.5	5.7
Evaporation (mm)	21.0	21.0
Change in soil moisture (mm)	- 15.3	- 6.9
Balance (mm)	- 3.49	-10.1

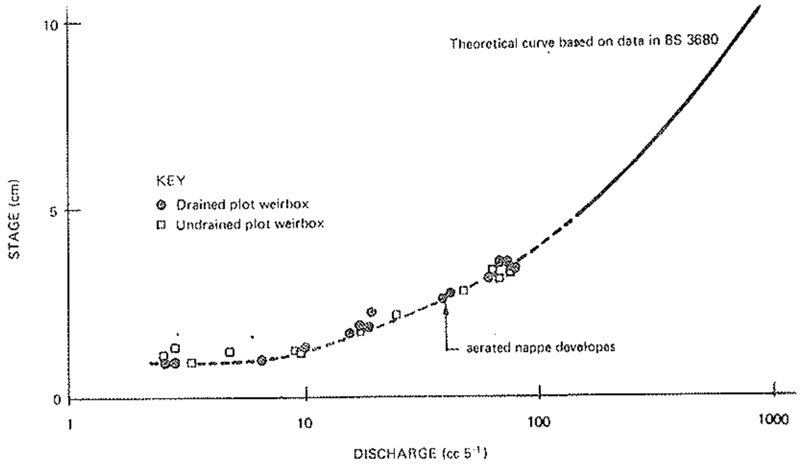


FIGURE 18 Calibration of V-notch weir boxes on drained and undrained plots

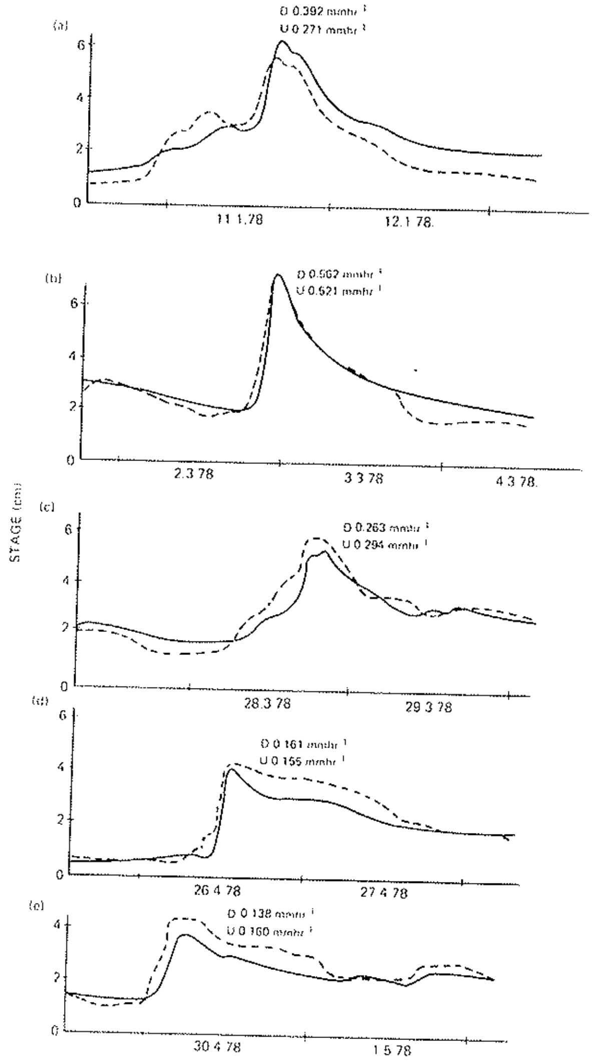


FIGURE 19

Selection of stage hydrographs for drained and undrained plot outflows, winter 1977/78, with peak discharges in mm hr^{-1}

Drained plot (D) solid line

Undrained plot (U) broken line

The drained plot, however, tends to show higher recession limb discharge from this plot. Reference back to Figure 15 shows that the tile drain on the drained site does affect the water table for some distance upslope, and it may be that the lower recession discharges from the undrained site are to some extent a result of the shallow flow collector not collecting a contribution to the ditch from flow in the clay beneath it. Yet, the mole drains of the drained plot should allow a much more efficient and widespread lowering of the water table while the continued presence of standing water over long periods on the undrained plot would suggest that subsurface flow rates are slow.

Indeed, in some ways the comparison between the sites is artificial, since in collecting flow from the undrained site the system is being changed. Figure 16 shows that the extent of surface saturation and standing water is greater where there has been no interference at all. However the fact that the difference in saturated area between the measured undrained site and the untouched area is not greater and

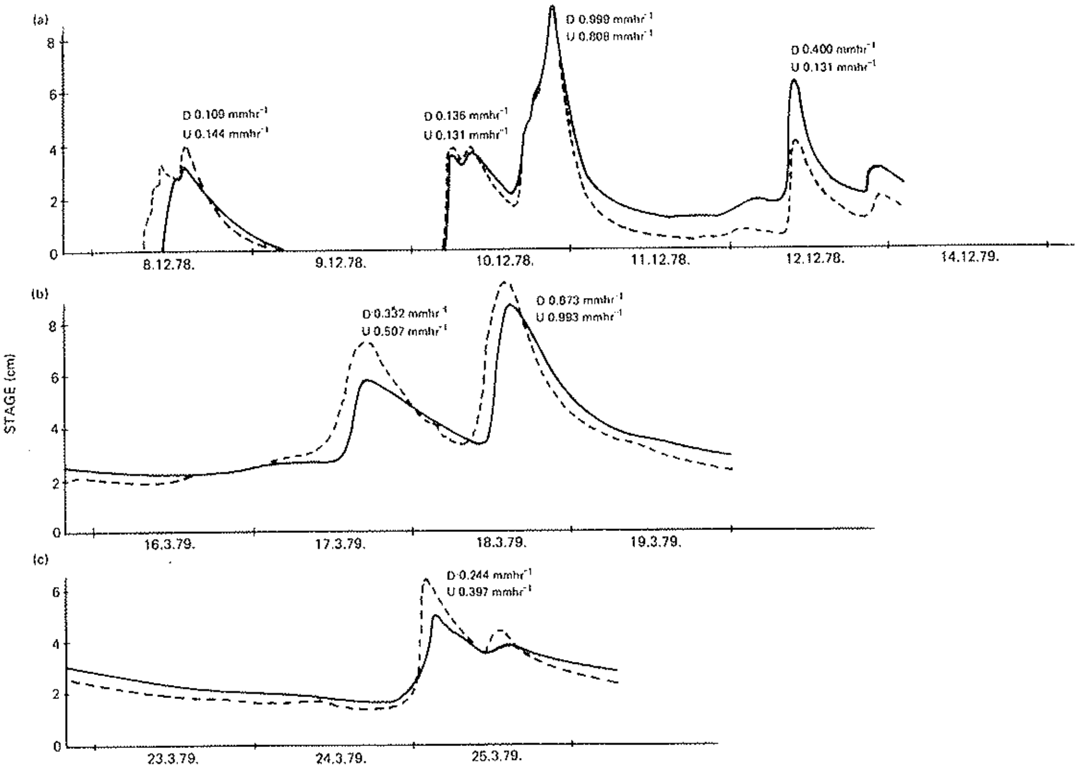


FIGURE 20 Selection of stage hydrographs for drained and undrained plot outflows, winter 1978/79, with peak discharges in mm hr^{-1}
Drained plot (D) solid line Undrained plot (U) broken line

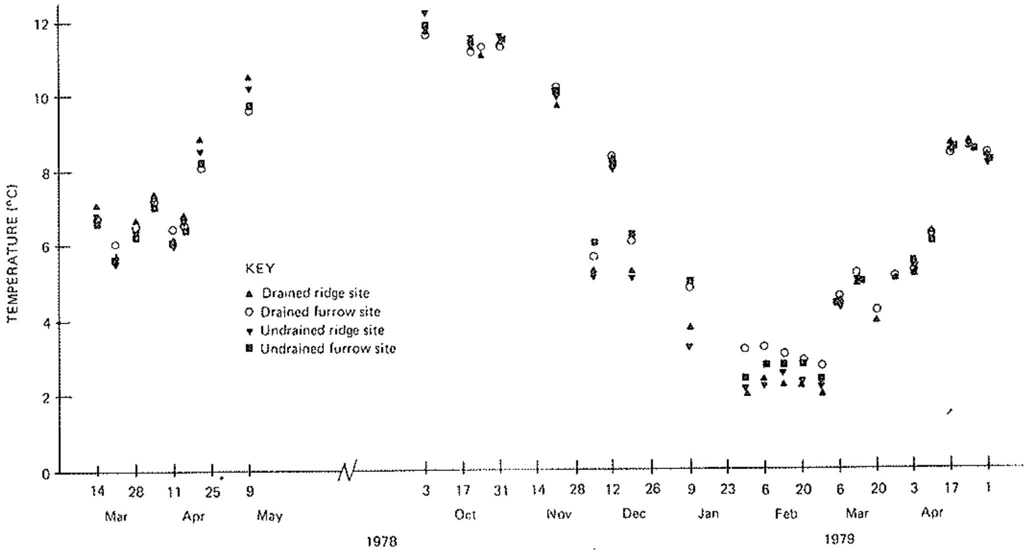


FIGURE 21 Plot of soil temperature measurements at 30 cm depth

showed no progressive trend over the winter, suggests that similar amounts of surface water find their way to the ditch during storm periods. The addition of the tile drain surface flow collector on the undrained site may change the timing of the hydrograph but the amounts should be roughly equivalent within the errors of sampling at one site rather than another. If the shallow tile drain collector does act as a faster route for surface water to the ditch (and weirbox) then it may speed the initial rise, increase the measured peak discharge and reduce discharges on the recession limb. If so, the effect would be to artificially increase the observed differences between drained and undrained plots. There is no way as yet of quantifying this effect relative to the differences between the measured plots.

Finally, the results of soil temperature measurements are shown in Figure 21. Differences between the four sites were small, with some tendency for the furrow sites to show a smaller range than the ridge sites on both plots. There was no consistent difference between the drained and undrained plots at this 30 cm depth.

7. THE MOVEMENT OF WATER IN CLAYLAND SOILS

The results of the plot experiments at Grendon Underwood provoke speculation concerning the movement of water in the clay soils of the plots, since while it is clear that the drained plot must dry more than the undrained plot between storms (on the evidence of soil moisture measurements, measured recession discharges and the absence of standing water), it seems that the drained plot is still capable of producing hydrograph peaks of similar magnitude and timing to the undrained plot. This implies that the additional storage made available by drainage between storms is not sufficient to slow the supply of water to the mole drains in comparison with supply to and transport by the predominantly surface water system of the undrained plot. The hydrographs of Figure 20a are of particular interest in this context since they represent the first hydrographs on both plots following the long dry autumn of 1978. At this time the furrows on the undrained plot have not yet reached saturation. In the storm of 8 December the undrained plot responds more quickly with a higher peak than the drained plot in keeping with the hypothesis that there is more storage to be filled before flow starts on the drained plot. However, on the following peaks the drained plot first equals and then surpasses the undrained plot. For further peaks on the 13th and 14th December the difference between the two plots was greater still but this may have been partly due to the effects of freezing conditions on the undrained site. This was one of few recorded instances when the drained plot provided significantly higher peak discharges than the undrained plot, presumably due to the fact that the mole drains already served as an efficient means of transporting water to the ditch before the surface flow system of the undrained plot had become properly established (standing water was not observed on the undrained plot until the beginning of January 1979 in this winter).

Thus it must be assumed that water can move quickly through the soil to the mole drains even allowing for the fact that surface flow on the undrained plot may be relatively slow compared with flow through the mole drains. At 45 cms depth the mole drains are well into the clay soil and lying only just above the compact clay that forms the parent material of the soil. The low hydraulic conductivity of the clay matrix would suggest Darcy-type flow into the drain, and that the curved water tables between drains, predicted by classical analysis applied in more permeable soils, cannot be a satisfactory explanatory mechanism in this case.

Two alternative mechanisms may be postulated. The first is that water runs over the surface until it can drain down the zone of relatively high permeability that lies directly above a mole drain and is remnant from the crack cut by the tine of the mole as it was drawn. These cracks were visible at the soil surface throughout the first winter, opened up as the soil dried in the summer of 1978, and while less clear could still be distinguished at the surface in the second winter of the experiment. The evidence of the overland flow collectors mitigates against this explanation, with very few instances of surface flow recorded on the drained site, suggesting that the infiltration capacity of the topsoil is sufficient to exclude the possibility of overland flow. In fact even on the undrained site, the surface flow collectors did not record flow except close to the area of surface saturation in the furrow suggesting that even here much of the flow contributing to the outflow may be of return flow type (water that has infiltrated into the soil before being forced back to the surface further downslope, perhaps by displacement).

A second explanation has been suggested by Trafford (Trafford and Rycroft, 1973; Trafford, 1973) who wrote:

> 'In many of our clay soils it is only in the topsoil that there is reasonably free water movement. In clays there is practically no interparticular water movement; all effective movement is confined to the cracks and fissures. In a fully swollen soil there may well be practically no effective cracks and hence no water movement. The installation of drains merely provides more outlets for the water moving in the upper layers allowing this to drain somewhat more quickly' (Trafford, 1973, p9).

Trafford suggests that water moves as lateral flow in the upper more permeable horizons above the clay layers that stay at saturation throughout the winter. This is a more reasonable explanation of the observed behaviour of the Grendon Underwood plots. The neutron probe measurements and the few tensiometer measurements available suggest that the water table between the mole drains falls only slowly between storms and that the profiles continue to wet up throughout the winter. This implies that water may continue to be absorbed by the clay matrix throughout this time, a suggestion that is backed up by field investigation that shows that the interiors of clay peds may not be saturated even at the end of the winter. This reinforces the view that any significant water movement in the subsoil must be through cracks and fissures.

There is certainly ample evidence that macropores are important in the movement of water through clay soils, evidence that has come primarily through the use of dyes to trace actual flow paths (see for instance Ritchie *et al*, 1972; Bouma *et al*, 1976; Anderson and Bouma, 1977; Bouma *et al*, 1977). These experiments indicate that water movement is restricted to a small volume of pore space that comprises the macropores and that water contained within structural units is almost inactive.

An experiment was carried out on the drained plot (on 8th May 1979) to investigate the nature of flow through the soil profile. A dilute solution of Rhodamine W7 dye was sprinkled on to the soil surface by hand sprinkler over an area about 1.5 m long extending away from the mole drain in the furrow of the drained site. Several intermittent doses of about 5 mm in one minute were added to an area of about 1 m^2 in total. A pit was dug to trace the path of the dye and it was discovered that there was no obvious zone of saturation in the soil profile except immediately around the mole drain. There was a small layer (∿ 5 cm) of general infiltration at the soil surface from which dye extended down in obvious fingers. All movement of dye below the topsoil was confined to cracks between the soil peds, and earthworm channels (which extended even into the compact clay subsoil at > 50 cm). One vertical burrow, 8-9 mm in diameter to a depth of 40 cm had also taken flow. The pit was started away from the dyed area, but lateral flow within the subsoil had taken place along three major interpedal lines. Flow was sometimes spread across all or most of the pedal faces and sometimes followed the lines of fine roots lying between the ped surfaces. Horizontal cross sections confirmed the general restriction of the flow to localised macropores below a depth of ∿ 5 cms.

Once the mole drain had been exposed a further dose of dye was added to the area adjacent to the pit, and took only 100 sec to generate flow in the mole at a depth of 45 cms, although previous applications may have established a network of water and dye filled fissures from which water could have been displaced into the mole. Further excavation of the mole did not reveal any major contributing fissures within the dyed area. In fact, within 5 cms of the line of the mole the shape of some ped faces appeared to be directing water away from the mole. It does not necessarily follow that the mole loses water in this way since the soil immediately around the mole was saturated and had lost its structure. This process may be initiated by smearing during the drawing of the mole but will be enhanced by the continued flow of water. The side was still in good condition at the end of this second winter although its bed was now somewhat irregular and its cross section was generally flattened in the vertical to an oval shape.

The dye was followed to a depth of about 60 - 70 cms when the clay became compact and was blue grey in colour with little mottling. At about 50 cms, there were large ped surfaces that were convex upwards and about 20 cm across. Here dye had appeared to mix with clean water already in the fissures between the peds, but had reached levels below the mole drain.

These results suggest that neither soil moisture measurements nor tensiometer measurements may be good indicators of water flow in clay soils. If the bulk of the water movement takes place in fissures which occupy only a small percentage of the volume of the soil then changes of water content in the macropore space will be within the error of measurement of the neutron probe, and the results of tensiometer measurements may be expected to depend on the position of the cup relative to the soil peds and fissures. Similar conclusions were reached by Kutilek *et al* 1976. The results of the dye tracing experiment would suggest that the water table in the fissures may respond quickly to rainfall and allow water to flow or be displaced into the mole drains. A similar mechanism may contribute water from the unsaturated ridge areas into the furrows on the undrained site. The possibility of flow in fissures to the tile drain independent of the moles is also raised. This is not likely to be significant at this present site due to the ridge and furrow topography which will direct flow down the line of greatest slope towards the moles. On the undrained site, the persistence of standing water suggests that any fissures in the subsoil do not allow significant flow and suggests that the mole drains, by effectively draining the fissures between storms, may maintain the pedal soil structure and thereby retain the fissures as water conducting channels over the winter. Nemec (1976) reports increases in hydraulic conductivity due to macropores or 'preferential ways' following drainage of a clay soil and suggests that the structure may not stabilise until several years after drainage. Such continued improvement may not be evident in the case of mole drainage, since the moles may be expected to deteriorate over time, decreasing the efficiency of the drainage system.

8. CONCLUSIONS

1. There is no significant evidence that increasing field drainage has affected the flow of the River Ray since records began in 1964.

2. The results of a plot experiment comparing the hydrological response of drained and undrained areas of ∿ 2500 m^2 suggest that drainage can both increase and decrease peak discharge depending on the nature of the storm and the antecedent conditions. Timing of peak discharges was generally similar on both plots.

3. Recorded recession discharges were always higher from the drained plot and led to a higher overall yield.

4. Drainage eliminated the occurrence of surface saturation and ponding of water which was common in winter on the undrained plot, so that although the hydrographs of the two plots were quite similar, the processes of response must be somewhat different.

5. It is suggested that water is transferred to the mole drains primarily through macropores in the soil taking up only a small part of the total pore space. These macropores are mostly interpedal cracks, root channels and earthworm channels. Drainage may help to maintain the macropores by draining them between storms and not allowing expansion of the clay to close them. The clay within structural units may not be saturated even at the end of the winter.

6. The results of the plot experiment must be restricted in generality due to the particularly marked ridge and furrow topography at the site; the necessity of comparing single plots without replication; and the limited time scale of the experiment.

ACKNOWLEDGEMENTS

This study was primarily initiated at the instigation of Frank Green. A D Bailey of the Field Drainage Experimental Unit gave some constructive criticism of an earlier report. Thanks are also due to the Georges, on whose land the plot experiment is located, and who have always proved extremely helpful and interested in the work.

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