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ON FLOWS FROM A CLAY SOIL—SEASONAL CHANGES AND THE EFFECT OF MOLE DRAINAGE

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ABSTRACT

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Six years' data were collected from a sloping grassland site with a clay soil. The high rainfall, together with a shallow topsoil on a much more impermeable subsoil, led to frequent surface saturation and a rapid storm response. A third of the annual rainfall was discharged in the surface 10 cm thick root layer of the topsoil. With artificial drainage by mole drains, surface layer flow was almost completely eliminated and, in winter and early spring, peak drain flows were less than surface flows from undrained land. However, the reverse was the case in the autumn when, following the opening up of shrinkage cracks in summer, there was rapid flow generation to the mole drains resulting in much higher discharges than those from the undrained site. This pattern was observed in each of the five years after drainage and was applicable for a wide range of storm sizes and intensities. Such seasonal behaviour is probably much more widespread than is generally realised.

INTRODUCTION

Agricultural drainage is an important method by which farmers can improve the productivity of their land. Drainage can lengthen the period when they can work on the land and increase the yield of the crops (Castle et al., 1984; Farr and Henderson, 1986). Much agricultural production is on clay soils, which despite being prone to waterlogging in winter are nevertheless fertile soils. It would be prohibitively expensive to install drains close enough to drain such soils and this has resulted in farmers using a secondary treatment to improve the structure (and drainage properties) of the soil above a wider spaced system of pipe drains. Subsoiling and moling offer two ways to improve soil structure. Subsoiling breaks up the soil in the surface 0.5 m or so, whilst, on more clayey soils, a system of unlined tunnels called mole drains may be formed. These mole drains will last for 3–10 yr before renewal and are linked to more permanent (40–50 yr) pipe drains by means of a permeable back fill over the pipes.

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Whilst suitable in many situations, moling requires certain criteria for success. Firstly, the soil must have a sufficiently high proportion of clay material for a stable channel to be produced; secondly, the ground must be sufficiently dry at the time of moling to enable adequate cracking of the soil above the channels and to prevent smear of the mole channel sides which could make them watertight. For many years mole drainage has been used in the low-rainfall claylands of eastern England (Childs, 1943), whilst, in the higher rainfall areas of the British Isles, it has met with less success. This paper reports a moling experiment in a high-rainfall area in western Ireland; the intention was to improve the agricultural productivity of some of the poorest land.

STUDY SITE AND INSTRUMENTATION

The study site near Ballinamore in Co. Leitrim (7°46′W, 54°04′N) has an average annual rainfall of about 1100 mm, distributed over about 240 days, and a potential evaporation (Penman short grass) of 450 mm. The soil is a surface water gley (Alfic Haplaquept) of the Ballinamore Series (A.F.T., 1973) and is typical of many of the glacial mineral soils derived from carboniferous shales in Ireland. The effective topsoil depth at the experimental site is 25–30 cm; this comprises a 10 cm organic clay loam surface (A1) horizon with abundant roots over a 15–20 cm layer of clay loam (A2g) with a subangular blocky structure. This grades into a structureless gravelly clay subsoil (Btg). The particle size distribution of approximately 45% silt, 35% clay in the topsoil changes to 35% and 45% respectively in the subsoil. The clay fraction comprises chiefly quartz, kaolin and mica with low montmorillonite. Soil-moisture retention curves for the surface 50 cm indicate that the range in soil-water storage capacity between saturation and pF 2.5 (a rough approximation to "field capacity") is about 50 mm. Due to the small pore sizes, capillary rise from the water table may help to keep the upper layers near to saturation in the early stages of drying, although the rate of rise is very slow. The root mat layer is quite permeable, whilst laboratory measurements of the saturated hydraulic conductivity indicate a value of about 0.3 m day^{-1} for the topsoil, with an abrupt decrease to 6×10^{-5} m day^{-1} for the subsoil. Roots penetrating along structural cracks in the subsoil provide evidence of the low permeability of the soil peds. Taken together, the high rainfall, the shallow topsoil with a low potential water-storage capacity (50 mm) and the very low subsoil hydraulic conductivity, help to maintain waterlogged conditions in the soil for much of the winter. Artificial drainage is thus a necessary first step to raising the level of agricultural productivity of this soil.

Two instrumented plots, each 22 by 2.4 m, were established on a 10° hillslope (Burke et al., 1974). The plots were isolated from outside surface-layer flows by a 30 cm deep open drain at the upslope end of each plot; in addition a 15 cm deep steel barrier was installed along the top and sides of each plot. At the lower end of the experimental site an eave and gutter, extending the width of each plot, collected flows from the surface root layer and led them to adjacent collecting tanks equipped with water level recorders. Surface layer flows from both plots were recorded for approximately 10 months as a "control" period to check that the plots were in fact hydrologically identical. Then, in April 1966, one of the plots was drained by two mole drains 1.1 m apart at 45 cm depth and flows from these two drains were led to a third collecting tank and recorder. Thus the surface layer flows from the undrained plot could subsequently be compared with those from the drained plot and with the drain flow. Flows from both plots were measured for a further $5\frac{1}{2}$ years until November 1971. Each collecting tank was one cubic metre in capacity, representing the equivalent of nearly 20 mm water depth over the plot. Water levels were continuously recorded on weekly charts with a time scale of 2.5 mm hr^{-1} and a vertical scale of 16 mm for every 1 mm flow from the plots. The tanks were emptied manually by opening a valve, when the charts were changed, and additionally when necessary during the week. On rare occasions, the tanks overflowed during large night-time rainstorms and flows were estimated for water balance purposes; in general, however, the record of water depths allowed storm depths and weekly flows to be calculated accurately. Shorter period flows could also be estimated by comparing the levels at smaller increments of time but, as the time step is reduced, sources of inaccuracy in timing and in measuring levels become more important. Consideration of the chart scale and the accuracy of the weekly clocks indicated that a one-hour interval was the shortest that should be used. To study soil moisture, tensiometers were installed in the middle of each plot at depths of 7.5, 15, 30, 45, 60 and 90 cm. Rainfall was recorded by a tilting siphon autographic raingauge equipped with a daily chart. The study area is under permanent pasture and, to prevent damage due to poaching by animal hooves, neither plot was grazed during the duration of the investigation, although the grass was cut by hand.

PLOT OUTFLOWS AND SOIL WATER REGIMES

Figure 1 shows the cumulative rainfall and flows for the two plots over the whole six-year experimental period. Prior to drainage, the surface flows from the plots were very similar in amount, given the inherent error in positioning the topsoil flow collectors at identical depths on both plots. When one plot was drained there was clearly a radical change in the flow mechanism from the plot. Table 1 summarises the main hydrological variables for the 5 yr following drainage. For the undrained control plot the surface layer flows averaged about one-third of the rainfall. The runoff coefficient varied from about 50% over the winter months (November–April) to about 15% in summer (May–October). In contrast, on the drained plot, surface flow was almost absent, less than 3% of the rainfall. Instead, the water was moving down the profile to the mole drains, the flow of which amounted to nearly 50% of the annual rainfall.

The mole drains largely eliminated topsoil saturation and surface layer flow and their effectiveness in controlling the water table was clearly demonstrated by the tensiometer data (Fig. 2). On the undrained plot the water table remained within 20 cm of the surface for long periods, whilst on the drained plot it was only infrequently above 40 cm, mid-way between the moles. An average lowering of 20 cm in the water table of a heavy clay soil was reported by Harris et al. (1984). Figure 2 shows the large range in water table depths in the dry

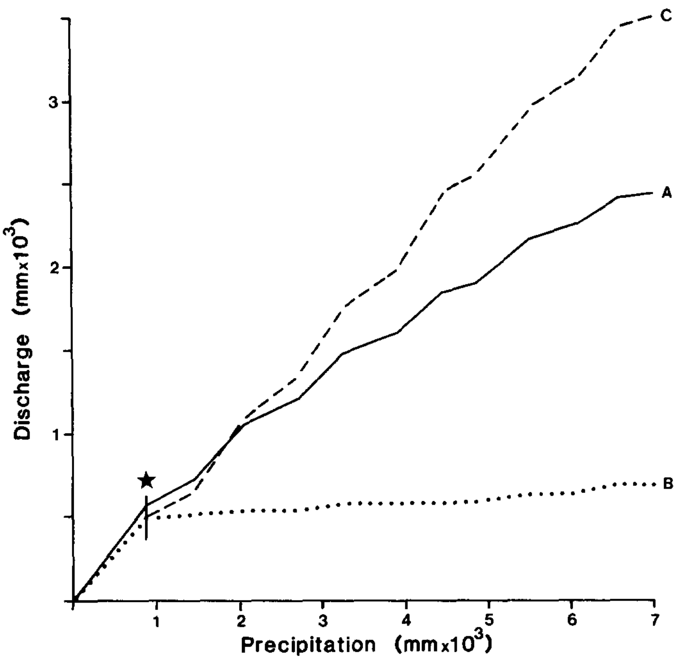

Fig. 1. Cumulative precipitation and outflow from the control plot (solid line, *A*) and experimental plot (broken lines) from November 1965 to October 1971 inclusive. The experimental plot was moled in April 1966 (★) when the flows from the surface layer (*B*) and mole drains (*C*) were separately recorded.

spring of 1968. The effect of the mole drains was evident in the wetter periods and even when the water table was below the moles it was deeper on the drained plot. The heavy rainfall in mid March resulted in a rapid rise in the water table on both plots, despite the very low hydraulic conductivity of the subsoil, and flow from the mole drains began 36 h before surface flow was recorded from the undrained plot.

STORM RESPONSES

During the 10 month calibration period, the amount and timing of storm flows from the two plots were very similar, confirming the uniformity of the

TABLE 1

Average annual depths (mm) for the 5 year period (1.11.66–31.10.71) following drainage of the experimental plot

	Rain	Potential evaporation	Undrained plot surface	Drained plot	
				surface	mole
Depth (mm)	1114	450	342	34	537
% rainfall	–	40	31	3	48

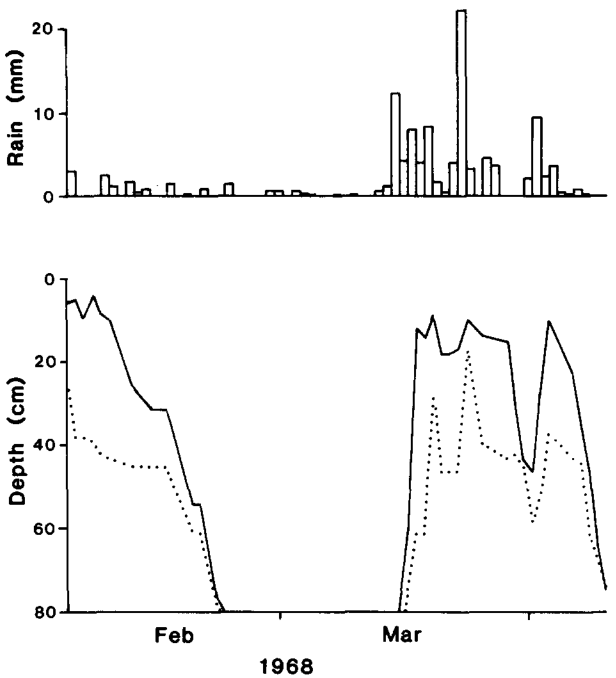

Fig. 2. Position of the water table on the undrained (solid line) and moled (dotted line) plots, based on daily-read tensiometers.

experimental site. Figure 3 shows the surface layer flows from the two plots for a typical sequence of storms. Runoff from the clay soil was very variable; little or no flow between storms rose rapidly to over 2.5 mm h^{-1}. The flow recessions were also quite rapid. The small differences between the shapes of the two outflows are within the likely inaccuracies in deriving short period flows from the cumulative flow recorders. Figure 3 thus demonstrates the nature of this small scale "noise" in the data, and indicates that, as regards the timing of peak flows, inaccuracies of one hour (the data interval between flow increments) are possible. There was no statistically significant difference between the plots in either the magnitude or timing of peak flows. Small differences in low flows between storms, which were higher from the control plot, were probably due to a slight difference in positioning the surface flow collectors on the two plots.

Following drainage, however, there was a consistent difference between the storm discharges from the two plots. Figure 4a shows a typical sequence of storm hydrographs in the first winter. Peak flows from the drained plot were much lower than from the undrained control, although, due to the higher baseflows, the total measured flows were similar (e.g., 76 and 71% of the rainfall, respectively, for the period in Fig. 4a). The ground surface was much drier on the drained area and it yielded negligible quantitities of flow from the surface layer.

Thus, despite the unmeasured flows below 10 cm depth from the undrained plot, its peak flows were consistently higher than from the drained plot in the

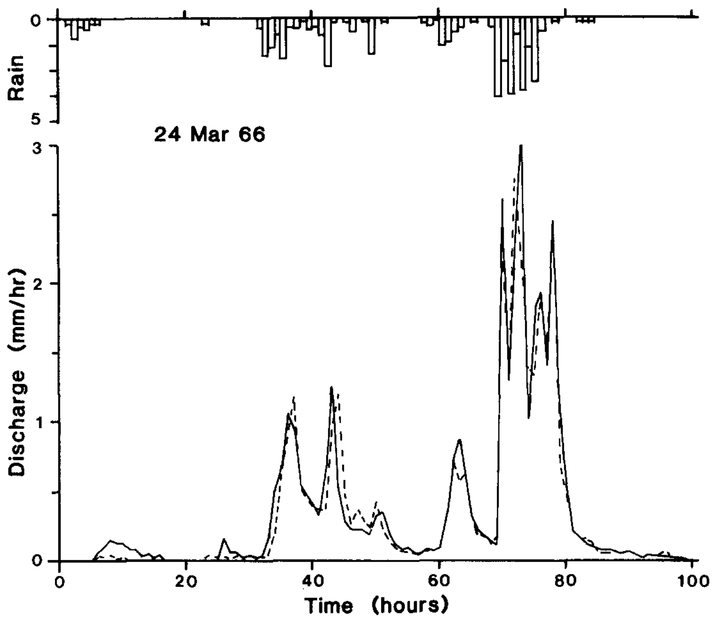

Fig. 3. Comparison of topsoil-layer storm flow from the control (solid line) and experimental (broken line) plots prior to drainage. Flows were derived as hourly totals, but for clarity are drawn as continuous curves.

winter period following drainage. The effect of the drainage was thus to increase the potential water storage capacity of the soil in storm periods through the enhanced rate of outflow in periods between storms. This reduction in peak flows from the drained plot could not be accounted for solely by any differences in the timing of maximum discharges to the surface flow and mole flow recorders of the drained plot. A reduction in peak flows due to drainage has been noted at a number of clayland drainage sites (Arrowsmith, 1983; Newson and Robinson, 1983).

Flows from both plots ceased for several months in the following summer; when they resumed in the autumn it was apparent that a change had occurred and that the drained plot was yielding higher peak flows and total flows (Fig. 4b). Low flows continued to be higher from the drained plot. As the site continued to wet up through the autumn, peak flows from the drained plot once again became less than from the undrained (Fig. 4c). This pattern was repeated in subsequent years (Fig. 4d), with the drained plot yielding higher flows in summer and lower in winter. To study this apparently seasonal behaviour in more detail, 70 storm events were selected from the 5 years' data after drainage. For each event a number of characteristics were abstracted, including the total storm rain and the maximum hourly fall, together with the total flow and the maximum one- and two-hour flows from each plot. The storm runoff coefficients for each plot showed a clear seasonal pattern, with a greater response to a

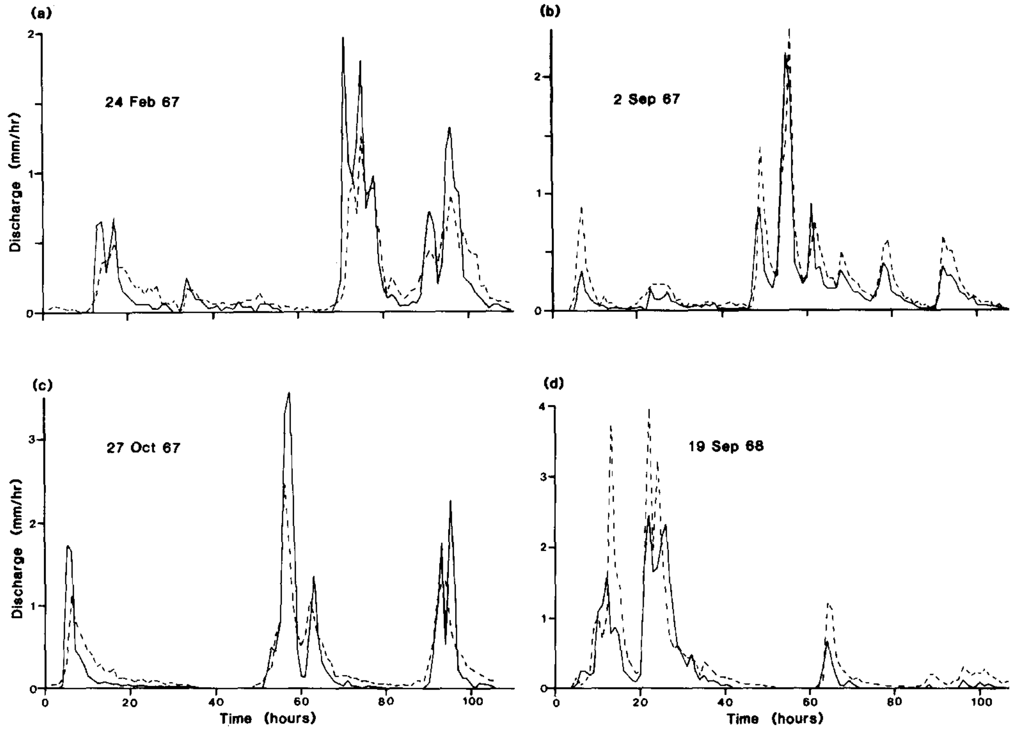

Fig. 4. Comparison of flows from the undrained (solid line) and drained (broken line) plots. In winter, (a) and (c), peak surface-layer flows from the undrained site were greater than maximum flows from the drained site. In late summer the drained-plot peaks were much larger, (b) and (d).

given rain depth in winter than in summer, although the percentages were very variable from storm to storm. When the flow volumes from the two plots were compared for each storm, there was no seasonal pattern to their differences; the drained plot generally yielded about 10–15% more flow, due to the higher baseflows. Peak discharges from the undrained land were usually much higher in winter than in summer; winter peak values of up to 5 mm h^{-1} were recorded. In comparison, maximum flows from the drained plot were generally lower, with most peak values below 2.5 mm h^{-1} except in the autumn, when rates of over 6 mm h^{-1} were recorded. Comparing the maximum flows from each plot for the same storm showed that in winter, the maximum drained-plot flow amounted to only about 70% of the undrained-plot peak flow, whilst in late summer/autumn this rose to 170%.However, such a comparison is very susceptible to high ratios for very small events, and a more meaningful measure was the difference in the peak flows (Fig. 5). In winter the peak flows were up to 3 mm h^{-1} greater from the undrained plot, whilst in late summer they were 3 mm h^{-1} smaller. A similar seasonal pattern was obtained from the storms in each of the years.

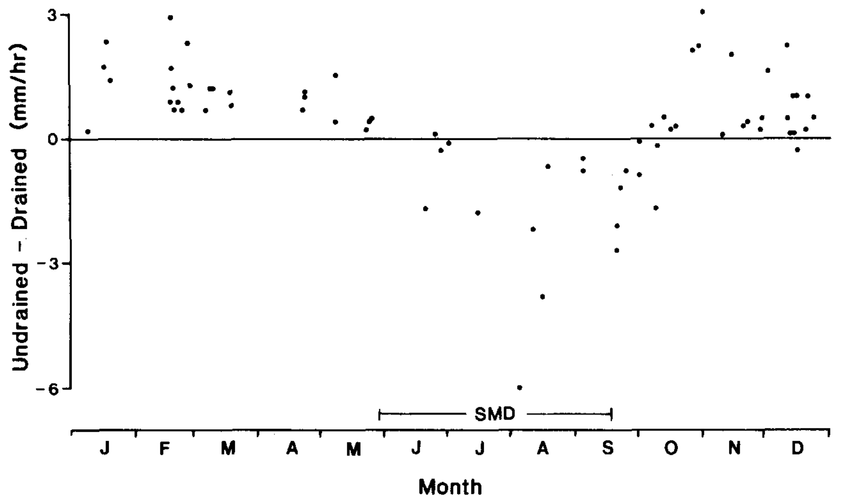

Fig. 5. Difference in peak hourly flows from the two plots at different times of the year. Data based on 70 storms, from June 1966 to November 1971. Points above the zero line indicate the undrained land yielded higher peaks in winter, whilst those falling below the line indicated higher peaks from the drained land in late summer. The average duration of soil moisture deficit is shown.

CAUSE OF SEASONAL CHANGES

Robinson and Beven (1983) observed a similar seasonal pattern on a clay soil in England. A dye tracing experiment at their field site showed that the peaky drain flows in summer resulted from rapid movement of the water through cracks and fissures (Beven, 1980). These cracks opened up during the summer as the clay soil dried out and closed up in the winter as the clay peds swelled up with increasing moisture content. Even at the end of winter the cracks between clay peds may not be completely closed. The critical importance of cracks in providing a route for water to reach mole drains in clay soils was demonstrated by Leeds-Harrison et al. (1982) in an experiment in which flows from a conventional mole drain were compared with those from a mole drain which had been created without associated soil fissuring. At Ballinamore in summer, the formation of shrinkage cracks allows rapid "short circuiting" from the surface to the mole drains, whilst in winter these cracks narrow down as the clay swells and saturation of the surface layers of the undrained plot results in higher storm peak flows. The effectiveness of cracks in promoting flow from very dry ground was demonstrated in a very intense storm in August 1971 (Fig. 6). The water table was at 90 cm depth on the undrained plot and below 100 cm on the drained plot when 40 mm rain fell in one hour. This generated a peak flow of nearly 10 mm h^{-1} through the drains, three times greater than the maximum surface flow from the undrained land. The total flow through the mole drains of 19.4 mm amounted to 42% of the storm rainfall, despite the soil moisture content being well below "field capacity". The surface layer flow was under 1 mm, whilst there was 9.7 mm from the undrained land.

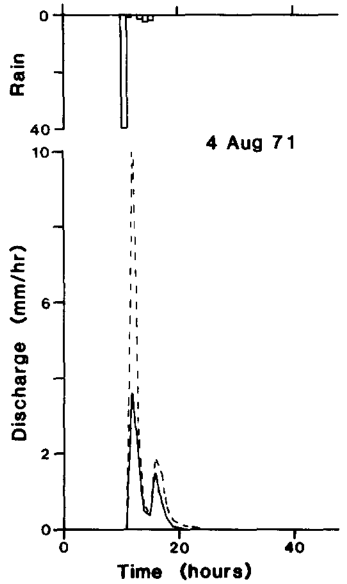

Fig. 6. Undrained (solid line) and drained (broken line) flows in response to a very intense summer thunderstorm.

Summer flows from dry, cracked, soils have been observed at other field sites (Harris, 1977; Reid and Parkinson, 1984) but information to predict the changing pattern of hydrological behaviour through the year has been lacking. To generalise the observations, the changes in flow mechanism must be related to the soil moisture history of the site. In the absence of regular direct measurements of soil moisture at Ballinamore, daily soil-moisture deficits were computed using the onsite raingauge records, assuming after Calder et al. (1983) a sinusoidal potential evaporation curve for the year. An annual potential evaporation of 450 mm, with a root constant of 50 mm and an available water capacity of 125 mm, indicated a soil moisture deficit for an average $3\frac{1}{2}$ months per year from late May until mid September. This agrees well with the pattern of cracking deduced from Fig. 5, except for the delay of almost one month between the estimated return to field capacity and the apparent closure of the cracks. That the cracks did not close for some time after the estimated return to field capacity is not unexpected considering the quantities of water flowing from the plots and not included in the budget calculations, as well as the time required for the cracks to decrease with soil swelling (e.g., Bouma and Wosten, 1979). Whilst the storm data for the individual years exhibited the same general seasonal behaviour, the hydrograph data provided evidence of differences between years of up to several months in the time of closure of the cracks. For example the autumn "wetting up" periods in both 1967 and 1968 had similar calculated dates for return to field capacity in mid August, but whilst in 1967 the cracks had largely closed by late September/early October (Fig. 4b and c), in 1968 they closed towards the end of November. Gravimetric topsoil moisture determinations confirmed the drier soil conditions in summer 1968, with values at the end of September of about 52% by weight compared with 58% in 1967, although, due to shrinkage, both these values are overestimates. Differences in rainfall totals could not alone account for the variation between years in the time from "field capacity" to effective closure of the cracks. More complex accounting procedures are needed, notably incorporating rainfall data at less than a daily interval, since there is evidence that in more intense storms a greater proportion of rainfall appears as bypass flow through cracks. There is less uptake by the soil matrix, so the amount of ped swelling is less and so is the rate of closure of the cracks (Fig. 6; see also Kneale and White, 1984).

SUMMARY AND CONCLUSIONS

The experimental data provide clear evidence in support of recent theories regarding the movement of water in clay soils. On undrained land, water movement is largely confined to the upper more permeable layer of the soil, with movement below being mainly restricted to flow in cracks. Mole drainage greatly increases the number of large pores and, perhaps more importantly, provides continuity of flow paths from the surface via the cracks to the mole drains and thence out of the soil. Surface saturation is largely eliminated in all but a few very large winter storms.

These cracks (both natural and artificial) are themselves subject to the natural shrink/swell properties of the clay and this will affect their ability to carry water (Bouma et al., 1979). As a consequence they are at their most effective in the late summer when the soil is at its driest; this effectiveness reduces with the wetter conditions in winter. However, as shown by the continued flow from the drains throughout the winter, the cracks do not close completely. An exception to this is in cases where the structure of the topsoil has been destroyed due to poaching by animals or machinery. In a mole drained area adjacent to the experimental site the drains ceased to function in two wet summers and were assumed to have failed but, after a prolonged dry period in the third summer, cracks reappeared and the drains functioned again (Gleeson, 1966). The mole drains had remained intact and, as with the study site described in this paper, just required a good cracking pattern to function efficiently. The fact that such seasonal cracks are so important hydrologically at this site despite the high and frequent rainfall and the mineralogy of the clay fraction, which is of low swelling potential, attests to the widespread nature of this phenomenon.

This study has demonstrated that a high rainfall regime does not necessarily preclude successful mole drainage. This has important implications for the potential of mole drainage outside of its long-held traditional areas, although, as found elsewhere in Ireland (Galvin, 1983), the degree of success may be very dependent upon the soil conditions and the soil moisture status at the time of moling. There are also environmental implications for the watercourses downstream. The increase in the available soil moisture storage due to drainage and the reduction in peak winter flows reduces maximum flows into river systems in the season of greatest flood risk. The clay shrinkage in summer and rapid flow response to autumn storms may, however, lead to an increased flood risk for small catchments in late summer. Such rapid flow through cracks and channels may also result in the rapid removal of herbicides or fertilizer (White et al., 1986), which may be both economically wasteful for the farmers and environmentally damaging to the receiving watercourses.

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