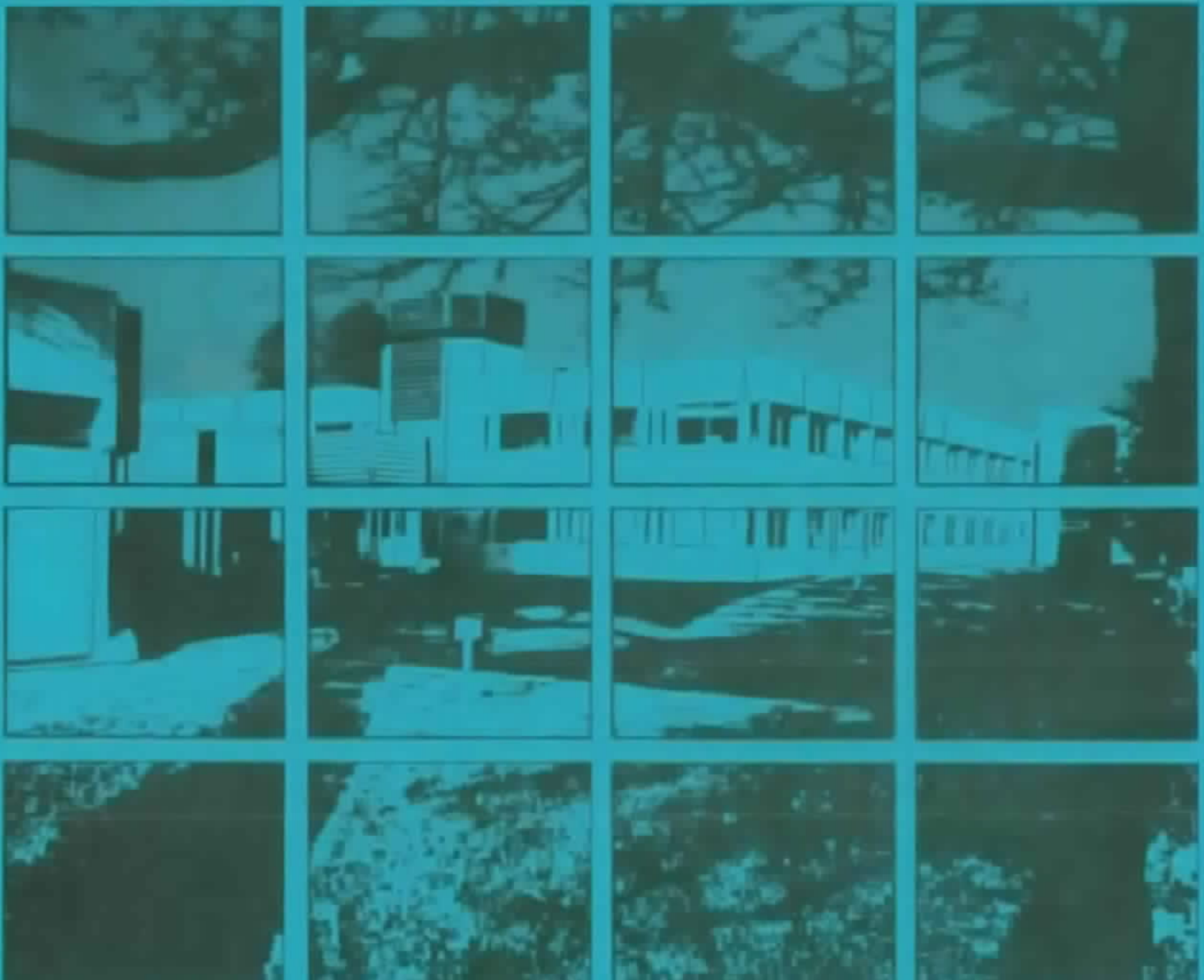
# INSTITUTE of HYDROLOGY

## Impact of Improved Land Drainage on River Flows



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# Impact of improved land drainage on river flows

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# Summary

The impact of land drainage upon the incidence of flooding downstream has long been a source of controversy. The main reason for the uncertainty has been the lack of suitable data. Consequently, a central part of this work has involved assembling a nationwide set of data from both published and unpublished field drainage experiments where flows were measured from both drained and undrained land.

It was found that, in contrast to previously expressed opinions, the drainage of heavy clay soils (prone to prolonged surface saturation in their undrained state) generally results in a lowering of large and medium flow peaks. This is because their natural response is 'flashy' with limited soil water storage available, whereas when drained, surface saturation is largely eliminated.

On more permeable soils, less prone to surface saturation, the more usual effect of drainage is to improve the speed of subsurface discharges, tending to increase peak flows. This finding is also at variance with earlier theoretical opinions, which assumed that due to their higher porosity, the storage buffer created by drainage of these soils would always act to attenuate maximum flows.

The results of this investigation emphasise the importance of the pre-drained response and indicate that the likely effect of artificial drainage (to worsen or reduce flood risk) at the field scale may be assessed from measurable site characteristics. These parameters include the soil water regime (if known) and the physical properties of the soil profile.

Computer simulation modelling of soil water and drainage system outflows using measured weather data, soil properties and drain parameters confirmed these findings of the field experiments. It further indicated the importance of rainfall regime: drainage reduces maximum discharges from higher rainfall areas. Baseflows were higher from drained than undrained land, principally as a result of the greater depth of the drains than the former unimproved channels.

At the river catchment scale, arterial channel improvements lead to larger flow peaks downstream, due to higher channel velocities and a reduction in overbank flooding and storage. This increase is greater for larger channel capacities and for bigger floods.

Studies of flow records from individual catchments indicate that the combined effect of field drainage and arterial works is to increase streamflow peaks (and dry weather flows) whether or not maximum flows are increased or decreased at the field scale. At the regional scale artificial drainage was a statistically significant parameter shortening catchment response times.

# 1. Drainage - a cause of flooding?

## 1.1 INTRODUCTION

A major change in recent years in Britain and elsewhere is the installation of field drains in farmland (Green, 1980a; Framji *et al.*, 1982). This report investigates the impact of artificial drainage on runoff, both as outflow from individual field-scale sites and at the river catchment scale. As Nicholson (1953) observed, 'The connection between field drainage and flooding in rivers has been a subject of debate for centuries'. And more recently in a review paper, Trafford (1978) stated 'The interaction of field drainage with arterial flooding ... is an area where more research is needed'.

This study encompasses a range of site characteristics and a consideration of the changes to both high and low flows. Britain offers a unique area to study the impact of drainage on river flows because :

a) Tile drainage originated in Britain (Van Der Beken, 1987), which is probably the most extensively drained country in the world (Green, 1979a);

b) It has unique documentary evidence of farm drainage, due to government grant-aid records (MAFF, 1986).

The land phase of the hydrological cycle is of profound importance, determining a wide range of processes, including the water supply to plants, recharge to aquifers and the movement of water and solutes to rivers. Artificial drainage of soils is a deliberate and direct intervention in this system, and an understanding of its impact is of importance for the practical and possibly legal consequences downstream of a drainage scheme. As noted by Thomasson (1975) : 'Any attempt to change the soil water regime of large areas of land will affect the general environment and to some extent the pattern of flow in streams and rivers'.

The hydrological effect of agricultural drainage was identified as a topic requiring further research at the ICE Conference 'Flood Studies Report - Five years on' (Johnson, 1981). Many people have highlighted the apparent inconsistency involved when the same government department (MAFF) is responsible for overseeing flood protection measures and has for many years been giving public monies in grant-aid to farmers (covering up to 70% of the cost of artificial drainage works) for schemes which could possibly result in increased flood risk downstream.

A study of the effects of drainage is of academic as well as practical value. It provides insights into the mechanisms and pathways of the land phase of the hydrological cycle, which are as yet still imperfectly understood (except under laboratory conditions!). Indeed, it may be argued that a valid way to learn more about the internal workings of a system is to observe its response to change.

## 1.2 CLAIMS REGARDING DRAINAGE

Debate about the downstream implications of drainage work followed soon after the beginning of extensive drainage work in the early nineteenth century. Some of the earliest recorded scientific work on this topic was by Bailey Denton who was concerned about the effect of drainage on flows for water power. His experiments are described in Bailey Denton (1862) and Beardmore (1862). A special meeting on this topic was held in 1861 at the Institution of Civil Engineers in London (Bailey Denton, 1862) and the discussion extended over four evenings.

Bailey Denton concluded that the result of drainage was 'rather to increase than to diminish the water supply'. Turning to extremes of flow, he said that he had formerly been of the opinion that drainage reduced minimum flows of rivers in summer, but had since changed that view and now felt that drying of the soil by drainage would reduce evaporation losses, resulting in more water being discharged in summer - 'as no water could be discharged from any drains, until the soil was filled up to the level of the drains, the subterranean supply could not be diminished, and that whatever water was rescued from the atmosphere was a gain to the rivers during the summer'.

In opening the discussion to Bailey Denton's paper, Mr G.P. Bidder, the President of the Institution of Civil Engineers, noted 'It was asserted in the paper that underdrainage did, to some extent, augment the flow of rivers, and thus necessitate a larger waterway under bridges, which were already barely sufficient; in that point of view the subject was one of great importance'.

In the discussion, varying views were expressed by the audience, many of which are still apposite today. The Rev J. C. Clutterbuck stated that 'the floods in the Thames, near Abingdon which used to reach their highest point in 72 hours, now reached that point in about 32 hours'. This reduction had occurred in both summer and winter, and he attributed it to the increase in agricultural drainage that had taken place over the previous 20 or 30 years.

Mr T. Hawksley also thought that drainage had a detrimental effect on streamflow, and said that from his experience everyone involved at a practical level with the collection of water was of the same opinion, namely: 'the more the land was underdrained, the more the irregularity of the stream was increased'. Whilst acknowledging that there might, be cases where this result did not occur, he went on to state that the normal condition would be that 'the river would be filled to overflowing at one period, and at another period the same river would be in a state of extreme and long-continued drought'.

Mr J.H. Lloyd, who was a director of a land improvement company, admitted that he also felt that underdrainage led to higher flows in winter and lower flows in summer. He considered it to be self-evident 'that at the time of greatest rainfall, when the natural flow would be greatest, they helped that flow, which was augmented by means of the artificial channels provided by drainage, and thus that greater floods were occasioned than had previously occurred'.

Mr R. Field differed from these opinions, arguing that for permeable soils the effect of drainage 'was clearly to reduce irregular surface overflow, and to substitute a more uniform discharge by percolation, as in chalk districts, and, consequently, its tendency must be to diminish floods, and to render the flow of rivers more regular'.

In his concluding remarks to the meeting, the President of the Institution of Civil Engineers, noted that 'With regard to the important question, to engineers, as to the effect of land drainage on the regime of rivers, he concurred with many of the speakers, that a larger amount of information was requisite, before it would be safe to generalise on the subject'.

Since then, with the question still unresolved, claims have frequently been made, following a severe flood, that the damage was made worse by upstream drainage. Examples of such cases include the following:

Thames (Ontario) floods of 1937 (McCubbin, 1938),

Severn (Wales) floods of 1946, 47, 48 (Howe *et al.,* 1967),

Scottish Border rivers in 1948 (Learmonth, 1950),

Hebden (Yorkshire) in 1974 (P. Roberts, quoted in Stewart, 1980),

York and Selby in 1982 (Caufield, 1982; Hansard, 1982).

Such views were not universally accepted, and many took the view expressed by Kendall (1950) : 'In my opinion the runoff from an area of well-drained land is spread over a longer period of time than from an undrained area of similar soil, the moisture holding capacity is higher in drained soil than in undrained, and the flood level of the rivers should therefore be lower'.

The Technical Panel of the Henage Committee examined the question of whether drainage increased or decreased flood risk to downstream communities, but it was also unable to reach any definitive conclusions due to the 'lack of observational evidence' (MAF, 1951).

This lack of information has hindered (or perhaps encouraged!) the discussions up to the present time, with farmers being blamed in the Press for increases in river flooding (e.g. Hart, 1979; Caufield, 1982; Rimington, 1982; Oldfield, 1983). Fishery interests in several parts of the country also maintain that farm drainage results in reduced summer baseflows (Morland, 1989). Green (1973) also expressed the opinion that drainage reduced baseflows due to a lowering of water tables.

In two recent scientific papers Rycroft and Massey (1975) and Bailey and Bree (1981) could find no published accounts of comparisons of flows from drained and undrained land in the United Kingdom. Their reviews of the international literature are discussed in detail in Section 1.4, but it is instructive that they could find only one suitable study : an investigation of drainage in northern Germany by Eggelsmann (1971); 'Eggelsmann appears to have been the only worker to have actually measured separately the outflow from full scale drained and undrained catchments' (Rycroft and Massey, 1975). It may be noted that these two 'full scale' catchments were 6 ha plots, delimited by boundary ditches, on a raised bog mire peatland.

There were, in fact, a small number of other published studies available at the time which were not mentioned in the reviews (e.g. Conway and Millar, 1960; Burke, 1968), but it was (and still is) correct that the available information from suitable sites is very limited. Somewhat suprisingly, Rycroft and Massey (1975) interpreted this lack of data as positive evidence against drainage adversely affecting river flows - 'There is no evidence to suggest that underdrainage increases flooding' - rather than as a lack of information to prove anything either way.

Part of the reason for this shortage of experimental data is that the interaction of drainage and river flows crosses the boundary between traditional engineering disciplines. River engineers were, until recently, concerned with the hydraulics of the channel systems and did not take a river catchment viewpoint. Their interest was in the movement of water in channels, and they knew little of the catchment attributes such as land use and soil properties. In contrast, agricultural engineers have been predominantly concerned with much smaller scale problems, mainly in-field, to remove 'excess water' in order to control the water table for better crop growth. Little attention was given to the downstreams effects on the arterial channel flows, or to the wider scale implications of their work on the environment. This attitude still continues, and even today for large-scale irrigation schemes abroad, little if any consideration is usually given to changes in the land use of the upstream water supply catchments. This led Higgins *et al.* (1988) to make a plea 'for investigations and studies into the hydrological implications of land use changes in watersheds. What do such changes mean to the downstream irrigation schemes? ... How will peak and low flows be affected by various changes in land use practices?'

Current academic opinion regarding the downstream effects of drainage remains divided. Some like Weyman (1975) and Ward (1978) believe that underdrainage 'helps speed up the movement of water towards the stream channels' whilst others consider drainage reduces maximum flows (e.g. Foster, 1989).

Much of the popular debate regarding possible changes in flow patterns is based on people's perceptions of changes over time in their natural environment - rivers appear to rise or fall more quickly, or more slowly, than before. Such qualitative and apocryphal claims must be treated with extreme caution, due both to the failings of human memories and to the fact that river flows may be subject to a multitude of factors, including a whole range of human influences in addition to artificial drainage (urban development, weed cutting and channel dredging for navigation etc.), as well as the natural variability of weather.

## 1.3 THEORETICAL ARGUMENTS

Arguments about the impact of artificial drainage on flows take many forms, but can be broadly divided into five aspects :

- the effect of an increased drainage density

- the effect of an enlarged available soil water storage capacity
- the effect of storm characteristics and antecedent conditions
- the effect of different types of drainage systems
- the effect of drainage extent and location within a catchment

### 1.3.1 Increased drainage density

Studies of natural stream channel densities have found a close correlation with measures of peak flows (e.g. Carlston, 1963; NERC, 1975). Higher drainage densities are correlated with peakier storm runoff hydrographs. This is because channel flows are much faster than throughflow or even overland flow. It has been argued by Howe *et al.* (1967) that this relation would also apply if the drainage density were increased artificially. Trafford (1973a), however, questioned the analogy since closely spaced artificial systems will reduce or eliminate surface runoff. He made reference to the opinion of E.C. Childs, that progressively increasing the drainage network will at first reduce peak flood flows, but that beyond a certain optimum drainage density additional drains will cause peak flows to increase. The optimum drainage density at which flood peaks are minimised was not quantitatively defined.

### 1.3.2 Soil water storage

In the absence of experimental data Trafford (1973) argued theoretically that artificial drainage of 'groundwater' soils, which are permeable but suffer from waterlogging due to rising groundwater, would result in lower peak flows. This was due to their large 'drainable porosity' - the volume of easily drained large pores. In contrast, he felt that the drainage of 'surface water' soils, such as clays, which have only a small volume of easily drained pore spaces may increase peak flows. Thomasson (1975) also agreed with this distinction based on soil type : 'It should not be thought that drainage measures inevitably cause more rapid runoff on all soils. In permeable soil, lowering the water table increases the temporary storage capacity of horizons above the water table. It also means that lateral water movement takes place through deeper horizons, and probably at a slower rate ........ on balance the overall effect should be to reduce peak flows'. He highlighted soils with an impermeable substratum as ones where research was necessary, particularly where secondary treatment was used. This distinction was also supported by Bailey and Bree (1981) using water table data for different soils, although they too lacked flow measurements with which to test their ideas. The special case of peat soils is discussed in Section 1.4.6.

### 1.3.3 Size and duration of storm

Given the creation of this extra storage capacity in the soil by drainage, the next question is when is this finite store filled up? The size and duration of storm that will exceed the extra storage capacity are clearly of importance. Pickels (1925) argued that 'In general it may be stated that up to the point of soil saturation the effect of artificial drainage is to decrease flood flows, whilst beyond this point it is to increase it'. Similarly, Hazen (1930) felt 'Drainage takes the water out of swamp soil and creates a storage space where none had existed. The effect of soil storage is greatest in taking care of runoff from summer or early autumn storms after the soil has been thoroughly dried out, but it may be much less with respect to late winter and early spring flood flows'.

Additionally, it has often been argued (e.g. Oberlin, 1981) that in very intense storms when rainfall exceeds the infiltration capacity of the soil, the effect of pipe drainage will be minimal, and drained and undrained land would behave in a similar fashion. This makes the tacit assumption that the infiltration capacity and surface storage of drained and undrained land are equivalent. This is not necessarily valid since drainage may accompany a change in land use with, for example, tillage of formerly unploughed land.

### 1.3.4 Type of drainage

A number of authors have suggested that there will be a distinction between the downstream effects of open ditches and of subsurface drains. Wisler and Brater (1949) argued that subsurface drains would lower the water table and increase the available subsurface storage, thus increasing infiltration. This storage would delay the movement of water to the stream, but 'On the other hand, if surface drains are present, the portion of the rainfall that becomes surface runoff is likely to reach the stream channels in a shorter time than it would without the surface drains'. Similarly, according to Pickels (1925) : 'when the small laterals of the drainage system are open ditches, the flood runoff will be greater than where large tiles are used for the laterals'.

The type of subsurface drainage may also be important : Numerous studies have found that peak flows from drainage systems comprising mole drains over pipe drains were much larger than those from a system of pipes alone (Trafford and Rycroft, 1973; Schuch, 1978). Both Nicholson (1953) and Trafford (1973) noted the very peaky storm hydrographs from mole drains and expressed the suspicion that mole drainage of clay soils could possibly produce higher maximum flows than from undrained land.

The capacity of a subsurface drain system will also have an important bearing upon maximum flows. Oberlin (1981) considered that drainage would increase flows up to the capacity of the pipe system; larger flows would be limited by storage routing, giving lower peaks compared to those from undrained land.

### 1.3.5 Extent and location of drainage

Clearly, in terms of influencing river flows the total amount of drainage in a catchment will be important, since 'The more adequate the drainage facilities, the greater the rate of flood discharge during excessive storm periods, especially those occurring during the winter and spring', (Pickels, 1931).

Wisler and Brater (1949) developed the argument further, stating that it was not just the amount of drained land in a catchment, but its distribution that was important for influencing flood flows : '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'. This expresses the importance of the timing of flows from sub-areas of a catchment reaching the outlet.

## 1.4 EARLIER REVIEWS

The previous section dealt largely with theoretical or subjective opinions; this section deals with reviews of the very limited available observations concerning the effect of drainage. Some of the primary references on which they are based are dealt with in more detail in Chapters 3 and 4 (Experimental studies) and Chapters 6 and 7 (Catchment studies).

The reviews are described in broadly chronological order. This is partly to reflect the, albeit small, increase over time in available data, but mainly to indicate how the reviews often rely heavily on earlier ones, and so cannot be treated as truly 'independent' assessments of the evidence.

### 1.4.1 Ministry of Agriculture and Fisheries (1951)

This Sub-Committee on Land Drainage Legislation looked at suggestions that land drainage operations (field drainage, moorland gripping and channel improvements) might affect the flow of rivers, and be 'at least a contributory cause of inundations on the one hand and water shortages on the other'. They were unable to make any general statement about the effects of either field or moorland drainage on river flows. Summing up, they concluded : 'it is possible to combine the many variable factors such as slope of land, surface cover, type of drainage, duration, intensity and pattern of rainfall, drain capacity, soil permeability and storage capacity, etc., in ways that will demonstrate the higher peak flow to be from either drained or undrained soil. Which of these ways is applicable to practical conditions cannot be decided, because field observational data do not exist in a sufficiently comprehensive form to make such a decision possible' (MAF, 1951).

They were more definite about the effect of river channel improvements : 'it must be conceded that the general effect of any local channel improvement which stops or reduces the inundation of adjoining land is to increase peak and near peak flows downstream'.

### 1.4.2 Howe *et al.* (1967)

The study by Howe *et al.* (1967), investigating the reasons for observed changes in flood frequency of rivers in mid-Wales, is in many ways a classic paper. They reviewed earlier work on studies of the effect of land use changes, such as forestry, on runoff and made a detailed examination of the available hydrometric data (both precipiation and runoff). By combining qualitative reports of increased peak flows after forestry ditching with the known empirical relationship between drainage density and flood frequency noted by Carlston (1963) they suggested that 'the introduction of drainage works in the upper Severn catchment has increased the amount and speed of runoff from major storm events'. However, when they examined the rainfall records they found an increase in frequency of occurrence that was 'of a similar order of magnitude to the increase in flood levels'. This created the problem of not knowing how much of the observed changes in flood frequency should be attributed to changes in climate. They could not resolve this fundamental problem so they concluded (Howe *et al.* 1967) that the increased incidence of extreme storm events had 'triggered' the increase in flooding, and this was 'aggravated' by the concomitant changes in land use.

It is of interest to note, however, how views once expressed, may become 'changed' over time by subsequent authors. Thus in a recent paper, Walsh *et al.* (1982) stated that Howe *et al.* (1967) 'attributed increased flood frequency in the Severn mainly to the large-scale afforestation in the headwaters of the catchment in the 1930s '.

Earlier, somewhat similar, investigations had been conducted by the Severn River Board following a number of severe floods which had produced claims that land use changes had been responsible (see Section 1.2). Rhodes (1950) reviewed the long term records of flood levels within the area dealt with by the Board, including those at Shrewsbury, Worcester, Gloucester and Bewdley. He found that there had been a considerable increase in the incidence of severe flooding and a marked increase in the rates of rises and falls in river levels. Whilst acknowledging that land use changes can affect runoff and may have 'aggravated' flooding conditions, he concluded 'The one unassailable fact that emerges from this investigation is that the degree of flooding or runoff is closely related to, and is a reflection of, the degree of rainfall'.

Following a major flood at Newtown, mid Wales, which also flooded parts of Llanidloes and Caersws, Haines (1965) examined flow and land use records. He concluded, like Rhodes (1950), that although land use and drainage changes may have some effect on runoff characteristics, their effect in this area had 'quite an insignificant effect on the magnitude of major floods'. In support of this he quoted grant-aid MAFF records indicating drainage of only a minor part of the catchment area upstream of Newtown : hill gripping (3.8%) and underdrainage (4.1%). The hill grips were 10-20 years old, and their effectiveness would have been much diminished. In addition, the Forestry Commission owned land amounting to a further 9.8% of the catchment, but much of this either had not been drained, or had drains that were old and no longer very effective in speeding the removal of water.

### 1.4.3 Rycroft and Massey (1975)

This paper, by MAFF's specialist Field Drainage Unit, has been very widely quoted, and is considered by many people (especially those in the agricultural community) to constitute 'proof' that drainage did not accentuate the flashiness of rivers (e.g. Lambert in discussion of Cole, 1976). Their conclusions were also quoted with approval by Beven (1980).

Following the lines of the argument by their colleague Trafford (1973), they dismissed the possibility of increased flooding from groundwater soils : 'The storage buffer created by the light soil effectively rules out the possibility that drainage of these soils contributes to flooding'. Rycroft and Massey concentrated their attention on clay soils, and adopted two main lines of argument.

Firstly, they used a model of flows from mole drains (Al-Soufi and Rycroft, 1975) based on the the ISO (input - storage - output) model developed by Lambert (1969) for the River Dee catchment. They compared the derived hydrographs for a number of storms with the observed flows from the Institute of Hydrology's Shenley Brook catchment, near Milton Keynes, which is on clay soils and known to be substantially undrained. The computed outflows from each field were lagged in time without any attenuation to yield a predicted catchment hydrograph for comparison with that actually recorded.

A comparison was made of the flows resulting from three consecutive storms over a four-day period in February 1974. In the first storm the predicted (mole drain) peak exceeded the measured (undrained land) flow; in the second storm the hydrographs were similar, and in the third storm the measured flow was substantially greater than the simulated drainflow. They explained this pattern in terms of the *likely* water table behaviour for the undrained land (it was not measured), suggesting it had been steadily rising towards the ground surface over this period until in the third storm the ground was totally waterlogged and rapid sheet flow predominated. In contrast, on drained land they expected the water table position to be largely controlled by the mole drains. Two interesting features of their results may be noted, and will be compared with actual measurements described later : (a) the total flow from the undrained land was much greater (over 25%) than from the simulated drained land; and (b) baseflows were higher from the undrained land.

Secondly, they analysed data from a field drainage experiment, on a heavy clay soil, in S. Ireland, where flows had been measured from undrained and mole drained land (Burke *et al.,* 1974). They showed higher peak flows from the undrained land, but did not mention that Burke *et al.,* (1974) previously concluded the opposite - that the mole drained land generally gave the higher peak flows. It was also not made clear that the plots were quite small, only 50 $m^2$ in area. As a result of the importance given to the Rycroft and Massey review by many people, but the fundamental inconsistency in the interpretation of data from the only site they could find in the British Isles, copies of the original experimental data were obtained from Mr Burke. The results of this re-analysis are described in Chapter 4. However, in view of the small size of the study plots Burke (pers. comm.) urged caution 'in interpreting the data in a broader hydrological context'.

At the catchment scale Rycroft and Massey quoted the conclusions of two very old studies : the Iowa and Des Moines rivers (Woodward and Nagler, 1929) and the Thames and Grand rivers in Ontario (McCubbin, 1938). Both studies reported no evidence of changes in river flows following periods of drainage. An examination of the two papers indicates, however, that the analyses of the data carried out were very crude. This is not suprising, given the date of these studies, and different conclusions might possibly be obtained using modern methods of analysis.

Noting that the very peaky hydrographs from mole drained land become lower as the mole drains deteriorate over time, Rycroft and Massey (1975) argued that since the drainage in a given catchment will be of a variety of ages it will exhibit a range of drainage efficiencies. Thus the overall hydrograph of even a completely drained catchment (not itself likely in practice) would be less peaky than from a single newly drained field.

### 1.4.4 Bailey and Bree (1981)

This review is essentially two papers; one by Bree describing the effects of large scale arterial channel improvements on river flows in S. Ireland and a report by Bailey covering many of the points previously made by his MAFF colleagues, Rycroft and Massey.

Bree showed that arterial drainage improvements in his study catchments shortened the time to peak and increased flood peaks - raising the 3-year flood value by about 60%. This work is described in more detail in Chapter 6.

Bailey adds some additional information to that of Rycroft and Massey (1975) regarding the difference between field drainage of groundwater and surface water soils. He suggested that drainage of the former might be expected to create an available water storage capacity of 80 mm compared with only about 20 mm for the latter. This is a consequence of both the deeper drain depths used and the greater drainable porosity of the more permeable groundwater soils.

Interestingly, Bailey was also puzzled that Rycroft and Massey (1975) concluded the plot data from Ireland showed drained reduced peak flows whilst Burke *et al.,* (1974) concluded the opposite. However, he was unable to offer an explanation.

### 1.4.5 Irwin and Whiteley (1983)

This review is of interest because it provides a north American perspective to the debate and some additional references. Nevertheless it is still heavily dependent upon the earlier papers of Trafford (1973), Rycroft and Massey (1975) and Bailey and Bree (1981). Irwin and Whiteley may not have consulted some of the primary references since, for example, they repeat the error that Eggelsmann (1972) studied full-scale drained and undrained watersheds, and they appear to think that the studies in S. Ireland by Burke and by Bree were carried out in the United Kingdom. Despite this, and the fact that a significant proportion of the studies quoted in the text do not appear in their reference list (and vice versa!), their review provides some useful information on additional studies, although none where flows were directly measured from drained and undrained land.

They conclude that field drainage 'is likely to reduce flow peaks for events which were preceded by a period of drainage during which tile drainage created a larger unsaturated soil depth than would have been present without tile'.

Irwin and Whiteley refer to work on mathematical modelling, but the studies mentioned are principally concerned with changes in surface depression storage, and so are not of general applicability. They refer to the same large river studies in the 1920s and 1930s used by Rycroft and Massey (1975) and give results of a more recent examination of the data series of the Thames river in Ontario up to 1980, which found 'small or zero' effects of drainage on streamflow (later published by Serrano *et al.,* 1985).

### 1.4.6 NERC Peat and Fen Committee

A Working Group of the NERC Hydrology Committee met between 1963-70 under the Chairmanship of E. C. Childs to discuss problems of blanket and fen peat. Although their findings were not published they did assemble a mass of interesting information, which was made available to this study.

At the outset, they decided to concentrate on blanket peat since this covered large areas of the country and there was concern with its effect on runoff; fen peat, in contrast, was seen as more of a localised problem and most interest in it was concerned with agricultural crops rather than its hydrology.

The Group had two main areas of investigation : (a) To map the areas of blanket peat. This was achieved by compiling information from various sources, including the Geological Survey of Great Britain, the Macaulay Institute, the University of Wales and the Geological Survey of Northern Ireland. The final map was, unfortunately, never published due to the costs involved (J.V. Sutcliffe, pers. comm.). (b) To study the effect of blanket peat cover on runoff. The Group did not undertake original work themselves, but reviewed information on studies that had been, or were about to be, carried out. They wrote to all the River Boards (in England and Wales), Purification Boards (in Scotland) and relevant Departments in the Universities (Civil Engineering, Agriculture, Botany and Geography). This survey included the effect of drainage on flows. It was widely noted, but not explained, that drainage of blanket peat at Moor House increased peak storm flows (Conway and Millar, 1960), whilst drainage of blanket peat at Glenamoy (Burke, 1968, 1975) reduced flow peaks. In their summing up of the replies received, the Group stated 'Where there is firm evidence or well based opinion, it seems to be conflicting, even to the point where different people describe the same evidence in different terms ... The unescapable conclusion, if the evidence is accepted, is that different things can happen in different circumstances and that these circumstances have not been recognised and reported on quantitatively'.

## 1.5 SUMMARY AND CONCLUSIONS

Many conflicting, but often apparently reasonable arguments have been made, which in the absence of reliable data have resulted in uncertainty and controversy for over a century. Much of the reason for these conflicting opinions lies in the relative importance given to two factors. Firstly, the ability of drains to carry water faster than subsurface flow through the soil (increasing peak flows). Secondly, the increase in the soil storage capacity created by the lowered water table (reducing peak flows). Opinions about the balance between these two factors are often based not just on scientific reasoning, but are also often influenced more than a little by 'vested' or 'political' interests.

Hence it appears that, in order to support a case, people are often very selective in the 'facts' they use. Both one and the other set of arguments have been quoted by supporters or opposers of drainage as establishing their position. Thus those town dwellers and conservationists who make claims that agricultural drainage 'speeds up' the movement of water to stream channels and increases peak flows downstream, usually point to the shortening of flow paths and the removal of former wetland areas where flood waters were stored. On the other hand, many farmers will use the argument that farm drainage creates an enlarged available soil water storage capacity which then acts as a 'buffer' to moderate peak flows. The lowering of soil water tables in drained land is often cited as evidence for this view.

Neither 'lobby' addresses the real question, the relative importance of these various factors. It is hoped that this report, building on the work of previous authors and using scientific analysis of a specially assembled data set, will go a long way to replace the emotive arguments by ones based on factual evidence. As Bailey and Bree (1981) observed, the effect of field drainage on catchment hydrology 'has been the source of much discussion over many years, but of relatively little scientific work'.

# 2. The extent of field drainage

## 2.1 INTRODUCTION

Before studying the impact of drainage schemes on the flows downstream it is necessary to understand some of the background to agricultural drainage works; why they are carried out, what is involved, and the extent of these schemes over the country.

## 2.2 PURPOSE OF AGRICULTURAL DRAINAGE

Drainage work comprises the improvement and maintenance, of 'arterial channels' by Water Authorities, Internal Drainage Boards, and local councils, and 'field drainage' by individual farmers. The latter consists of the installation of in-field drains and the cutting of field ditches, and is the principal subject of this report. Surveys of the extent of arterial drainage channels in England and Wales have been given elsewhere (Marshall *et al.*, 1978; Brookes *et al.*, 1983) and will not be discussed further here, although their hydrological effects are described in Chapter 6.

Most plants have become adapted to survive in a particular environment, and crops are no exception. To grow successfully at a particular site they may, for example, need the addition of extra nutrients or water. Similarly, if the soil is too wet, this may inhibit plant growth. The installation of artificial drains to remove 'excess' water from the soil confers a number of benefits to farmers on wet land (Mitchell, 1898; Castle *et al.*, 1984; Farr and Henderson, 1986). These include :

(a) Better aeration in the plant root zone promotes the uptake of nutrients and encourages plant growth,

(b) Drier soils warm up more quickly with earlier emergence and ripening of crops and increased bacteriological breakdown of organic matter in the soil,

(c) More uniform crop growth over a field,

(d) A greater variety of crops may be grown,

(e) Deeper root growth increases the available zone for obtaining plant nutrients and makes plants less susceptible to 'drought' conditions in dry summer periods,

(f) Plants are healthier and less prone to disease and pest attack,

(g) Less mechanical power is necessary for tillage operations,

(h) Greater bearing strength of the soil increases the time of the year that heavy machinery can be used on the land and reduces soil compaction damage,

(i) Less poaching damage of grassland enables a greater stocking rate of livestock,

(j) Reduction of animal diseases associated with wet pastures.

Drainage of wet ground has been said to increase yields of a wide range of crops by 10-25% (Castle *et al*, 1984). It also gives the farmer much greater flexibility in the timing of operations.

## 2.3 HISTORY OF DRAINAGE IN BRITAIN

Field drainage in Britain probably dates from Roman times, but it is only in the last 200 years that significant amounts have been carried out. Enclosure of the common lands beginning in the seventeenth century was a necessary precursor to agricultural improvement. From about 1750 there was an increase in the amount of drainage carried out. The drains at that time were mainly made of stones, brush wood, peat or bands of twisted straw; it was only from the beginning of the nineteenth century with the invention of clay drainage pipes that drainage became more widespread. The price of drainage varied across the country with the availability of the raw materials - clay for the tiles and coal for the kiln. Contemporaries noted that in some areas 'a high price of draining tiles is almost prohibitory of draining' and if a means could be found to reduce their cost of manufacture 'no thing could be more advantageous to English husbandry' (Pusey, 1841). In 1845 Thomas Scragg invented a machine for extruding drainage tiles, which brought their price down by some 70%. This began a period of intensive drainage which continued for about half a century, helped by loans from government and private sources. About £12M was loaned in the period 1850-78 by government and private drainage companies, besides many landowners draining their land with their own money. This was a period of agricultural prosperity and expansion, the so-called era of 'High Farming', with expanding markets due to population growth and the railways. Drainage played an important role in this period, being termed 'the great improvement of the age' (Chambers and Mingay, 1966). Towards the end of the nineteenth century, however, there began a period of agricultural depression, with increasing competition at home (due to the opening up of much virgin land in the USA to agriculture by the railroads) and the erection of tariff barriers by other European countries. Britain, however, continued to adhere to 'Free Trade'. During this period of agricultural depression which began about 1880 and continued until the 1930s very little drainage was carried out (Nicholson, 1943; Adkin quoted by Trafford, 1970).

In recent years, under government policy of support for agriculture (Bowers, 1985) including grant-aid payments towards the cost of drainage, technical advice and price support for agricultural produce there was considerable renewed interest in farm drainage.

### 2.3.1 Nineteenth-century drainage

There is little information on the amount of drainage in the nineteenth century, and what historical records that do exist, are conflicting and contradictory. The most frequently quoted source is the evidence which Bailey Denton (1881) submitted to the Agricultural Commission in 1880. He stated that in England and Wales about 4,000 $km^2$ had been drained using government loans, and estimated that in addition perhaps twice that amount had been drained with private finance. The area drained by government loans may be calculated from records of the sums of money loaned, but estimates of the amount of privately funded drainage are very uncertain. They have often simply been assumed to be a particular multiple of the government financed drainage. What value this multiple should be is, however, not accurately known. Denton changed his estimate from 1 to 2 (Bailey Denton, 1873, 1881) and Caird (1873) assumed the ratio of public to private finance was a factor of 3. This uncertainty gives rise to a range of estimates of the total drainage in England and Wales from about 8,000 $km^2$ to 18,000 $km^2$. In a review of the contemporary sources of evidence, Phillips (1969) was forced to conclude 'It is unwise to put any confidence in estimates which are so variable and unreliable .... The acreage drained during the period 1850-80 is unknown'. More precise evidence is available for some local areas from the records of large estates (e.g. Phillips, 1972) but it would unwise to extrapolate their drainage rates to surrounding areas since these estates often had the money and labour available to carry out this work, and so were not necessarily typical of their locality.

Trafford (1970) examined Denton's records and considered that a more reliable figure for the area drained in the nineteenth century could be made from estimates of the number of clay tiles manufactured at that time. By assuming a average of 3,100 pipes needed to drain each hectare, and allowing for sales overseas, he concluded that about 50,000 $km^2$ had been drained. This figure is considerably higher than the estimates made by Caird and Denton. In support of this high value, Trafford (1970) referred to a survey of drainage need carried out by the MAFF, and published in the following year (Belding, 1971). In this survey, a randomly selected sample of maps, corresponding to 5% of the land in England and Wales, were given to the local ADAS field drainage advisors. They assigned the land in their area to the following categories : (i) drained since 1939, (ii) naturally free draining soils, (iii) adequate drainage by old (pre-1939) drains, (iv) in need of drainage, and (v) uneconomic to drain. The results of this survey indicated that about 21,000 $km^2$ relied on old (pre-1939) drains. Since there had been little drainage in the early part of this century, Trafford argued that this figure of 21,000 $km^2$ might reasonably represent the remnant of up to 50,000 $km^2$ drained in the nineteenth century.

Thus, far from identifying which nineteenth century estimate was the more accurate, the work of modern agriculturalists have cast doubt on all the estimates by calculating an area of drained land which is greater by a factor of between 2.5 and 6.

### 2.3.2 Twentieth-century drainage

Many of the nineteenth-century drains had reached the end of their useful life following the First World War (Mackay *et al.,* 1973). Government grant-aid payments towards the cost of drainage work (including field pipes and ditches, open hill drains on the moorlands and arterial channels) were introduced in 1921 in Scotland and in 1939 in England and Wales and marked the start of relatively reliable records of drainage work carried out.

Due to the important role of drainage in efficient agricultural production there has long been government assistance to farmers installing field drainage, both in terms of grants towards the cost and technical advice on drainage design. This involvement of of the government with drainage grants has resulted in a centralised record of drainage payments and areas drained. With grants that were typically 50-60% of the cost, very few schemes went unrecorded (Trafford, 1970), and the records provide a very complete picture of drainage activity. These data were collected in Scotland by DAFS and in England and Wales by MAFF. These two organisations work largely independently; as a result, their data are not always as compatible as might at first be thought. Thus whilst it was originally intended to analyse them together, it was found necessary in this report to deal with their data separately. Some comparisons are made, however, and apparent anomalies discussed.

Under the government's policy of support for agriculture and stimulated by high rates of grant, the uptake of field drainage increased steadily. It reached a peak of about 100,000 ha/year in England and Wales in the 1970s (Fig 2.1). Due to the recent government policy of running down support for

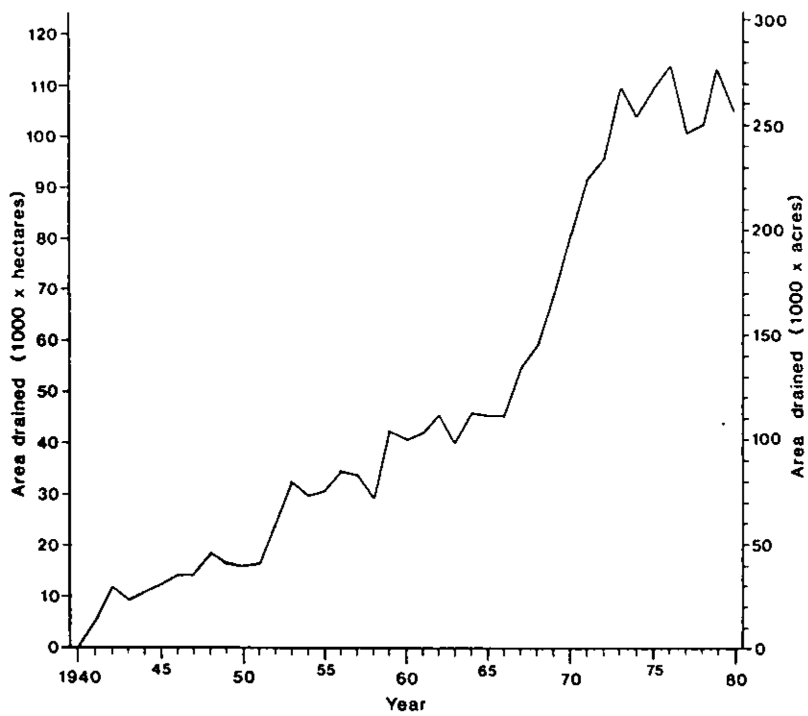



*Figure 2.1 Annual area of grant-aided underdrainage in England and Wales, 1940-80*

agriculture and reducing the numbers of agricultural advisors, no reliable data on drainage rates are available after 1981. Current levels have been estimated at under 50,000 ha/year (Stansfield, 1987) or about 40,000 ha/year (Trafford, 1987) i.e. only about half the maximum rate in the mid-1970s. This decline has resulted from a number of factors. Increasing concern for the environmental effects of intensive agriculture and the rising surpluses of agricultural production in the EEC, have resulted in recent years in a reduction in the level of government support to agriculture. Combined with production quotas and an uncertain economic future this has led to a reduction in farm expenditure, including that on field drainage.

In Scotland, grants for field drainage (and hence centralised records) were initiated in 1921 as part of a scheme to alleviate rural unemployment and were at first paid by administrative arrangements with the Treasury. Government support for land drainage works has continued without interruption since that time. Eligible schemes include ditching, underdrainage, hill drainage and minor arterial works (Mackay *et al.*, 1973).

The annual area of farm land underdrained in Scotland from 1922 to 1988 is shown in Fig. 2.2. There may be some inconsistency in the figures due to changes over time in methods of describing the various works and classifying expenditure so that it is difficult, now, to allocate recorded total expenditure to work on arterial channels, farm ditches, moorland drainage and to

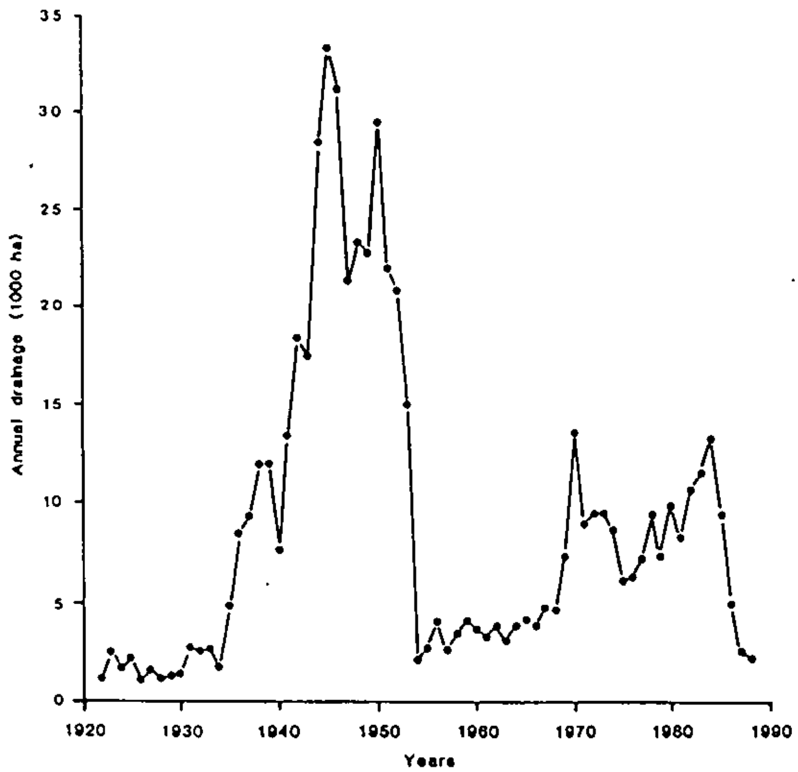



*Figure 2.2 Annual area of grant-aided underdrainage in Scotland, 1922-88*

underdrainage. Furthermore, there would have to be a degree of subjectivity in the identification of area of benefit ascribed to works associated with the improvement of outlet channels. Areas of benefit are reliable only where underdrainage is clearly separated from other categories of improvement and this was true only from 1977. As far as possible, however, the data used in compiling Figure 2.2 attempt to exclude categories other than underdrainage (Robinson *et al.*, 1990). Current (post-1982) data are based on a special land drainage survey for the specific purpose of establishing trends in land drainage.

The greatest activity occurred during the war years and just afterwards. Increased agricultural production was encouraged during the 1940s as part of the war effort. These annual totals show a great deal of fluctuation which is difficult to explain. In principle the amount of land drainage is closely dependent upon the perceived prosperity of agriculture on the part of farmers. The abrupt swings evident in the graph, however, imply that other factors may also be responsible; certainly the records for England and Wales show a more regular pattern over time.

Green (1974) found the large increase in drainage activity in Scotland between 1934 and 1954 'so surprising as to be virtually incomprehensible' and suggested that perhaps a transcription error of a factor of 10 had occurred in the DAFS's records! However subsequent investigations by DAFS could find no such error. The marked downward swing of drainage activity in the early 1950s is also shown in the totals of expenditure eligible for grant, so that, notwithstanding any complications in recording drainage activity, the downturn is real. It may be that assessment of area of benefit was overstated in the wartime and immediate post-war years and the extreme peaks of that time should be attenuated.

Mackay *et al.* (1973) noted that these fluctuations coincided closely with changes in the eligibility of certain types of drainage, with maintenance work to existing schemes excluded from the early 1950s until 1968, corresponding to a period of low recorded activity. This appears to offer a logical explanation for the recorded variations, with the wartime agricultural expansion (including the renewal of former agricultural lands) being followed by a second burst of maintenance work, around 1950, whilst grant payments (50% of the cost) were still available. Following a period of low drainage activity, maintenance grants became available again after 1968 (but only for those schemes that had not previously had payments for maintenance). Thus changes in eligibility may, in part, account for the swings in drainage activity, but a full reappraisal of the Department's data to resolve these opinions is beyond the scope of this report.

From the time of the marked downturn in drainage activity in the 1950s there was a much more regular pattern, with a fairly steady increase in the 1960s and 1970s, a period of agricultural growth and prosperity, and which is also apparent in data south of the border. The decline in the current rate of drainage reflects, as in England and Wales, the general reduction in farm expenditure resulting from an uncertain economic future for agriculture, beset with production quotas, and reduction in government support, as well as the increasing concern about the environmental effects of intensive farming methods.

## 2.4 DRAINAGE SYSTEM TYPES

Various methods have been used over the centuries to try to improve soil water drainage for agriculture. The most primitive technique was to plough the land into large scale ridges and furrows, some of which can still be seen today in old grassland. Open ditches have long been used to drain fields but they have the disadvantage of splitting up the land into small areas and are used mainly as outlet points for drainage water along the margins of fields.

The only effective land drainage technique which does not disrupt field cultivation is a system of sub-surface pipes. This is the principal form of in-field drainage; it is commonly (although somewhat confusingly) known as 'underdrainage'. In contrast, on the economically more marginal moorlands and hills underdrainage is too expensive and only the cutting of open ditches can be justified; this is discussed separately in Section 2.6. Similarly, the effects of the farm ditches which carry away the water discharged from the field drains are described, together with improvements to larger arterial channels, in Chapters 6 and 7.

Field drainage techniques generally rely on the installation of drains in the soil to remove water from the saturated zone, below the water table, through the action of gravity. This is water that may be considered to be in excess of 'field capacity'. The drains provide a means for this water to leave the soil more quickly than would otherwise be the case. They do not, and cannot, remove water other than that which flows into them freely under gravity.

The type of a drainage problem (i.e. the cause of soil water saturation near to the ground surface) at a site is traditionally divided into one of two categories, depending upon the source of the water. These are high groundwater, which is usually associated with permeable soils in basin situations, and surface water or perched water problems in which the surface layers are saturated due to the low permeability of the soil (deeper layers may be unsaturated); this is most usually the case with clay soils. Details of drainage techniques are given in a vast number of drainage texts (e.g. Eggelsmann, 1978; Smedema and Rycroft, 1983; Castle *et al.*, 1984: Farr and Henderson, 1986). The following sections give only a brief background summary of British conditions.

### 2.4.1 Drainage layout

The cause of waterlogging clearly affects the design of drainage systems adopted. Thus the layout of the drains may comprise one or more 'interceptor' drains placed along a springline, or a 'random' layout with pipes draining specific depressions and other wet areas. The most common form, however, is the 'comprehensive', 'systematic' or 'regular' layout with regularly spaced parallel lateral drains. These feed into a collector or main drain, which in turn will discharge into an arterial drainage channel.

The design of a regular drainage scheme varies with a number of factors including the drainage problem and soil type. Thus in broad terms slowly permeable surface water soils, such as heavy clays, are drained at close spacings of 5 to 15 m, whilst more permeable soils with groundwater problems are drained at wider spacings of up to 40 m. The necessary spacing for soil water control also depends on the depth of the drains; generally deeper drains allow a wider spacing, and there is usually a range of depth/spacing combinations that will achieve a desired control of the soil water regime. In practice there are often physical and economic constraints on the range of drain depths possible at a given site. For surface water soils the useful drain depth is limited by the thickness of the more permeable upper layers of the soil, whilst for high groundwater soils the maximum drain depth may be limited by the outfall channel. In many clay soils the subsoils are so impermeable that there is little point in laying pipes deeper than 75 cm. In permeable soils drains may be installed as deep as 120 - 150 cm.

There is now a great body of research regarding field drainage design (see Framji *et al.*, 1983). In Europe the most widely used drain spacing formula is the Hooghoudt equation (see Section 5.2.2). This gives the drain spacing from the design rainfall, soil hydraulic conductivity, drain depth and water table depth. Nevertheless it is true to say that such scientific methods are not widely used in Britain. Most farmers prefer to use local 'traditional' drain spacings they have used before or have seen to produce satisfactory results on neighbours' land. Thus 'in practice, most designs are based on the experience of the drainage of similar soils' (Castle *et al.,* 1984). As a result there are many areas where 'drainage treatments vary quite considerably in what appear to be similar soils and cropping situations'. Information about the drainage designs used on soil series in different areas is given in Armstrong and Smith (1977) and SSEW (1983).

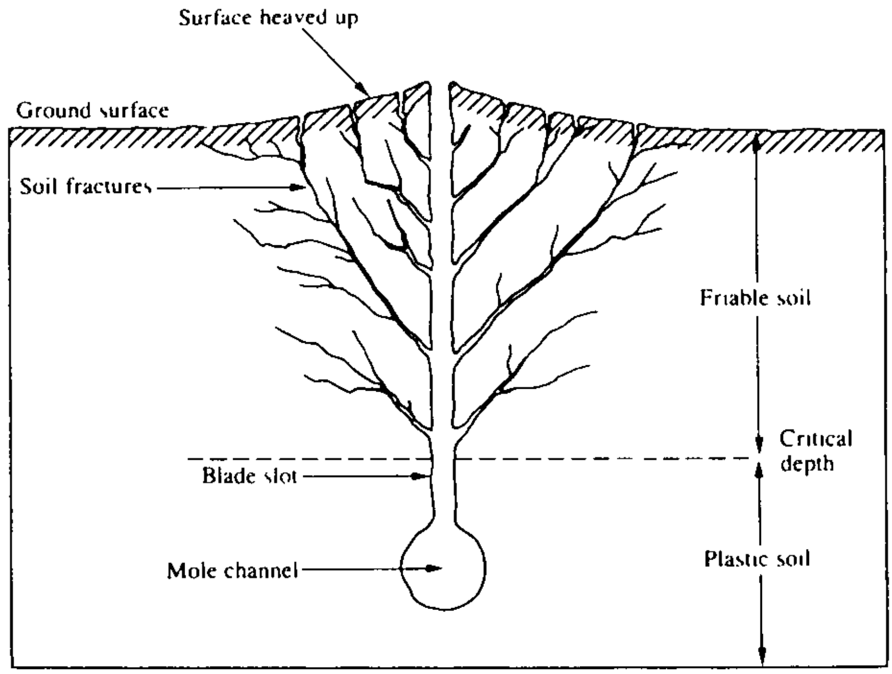
### 2.4.2 Secondary drainage

In clay soils the required drain spacing is often so small that pipe drainage would be prohibitively expensive. In such soils the subsoil properties above the drains may be modified by mechanical means to facilitate the movement of water to the pipe system. A 'secondary' treatment comprising 'moling' or 'subsoiling' is carried out at close spacings, say 1 or 2 m, over much wider spaced (e.g. 30 or 40 m) pipe drains.

The objective of subsoiling is to provide a general loosening of the subsoil by lifting and shattering, thereby introducing an artificial structure. On the other hand, mole drainage is carried out at deeper depths where the overburden pressure is sufficiently great to prevent a general uplift of the material, and instead a channel is formed with only a small amount of fissuring above it. In soil mechanical terms, subsoiling acts above the critical depth and mole drainage below (Spoor and Godwin, 1978). The different effects of mole drainage and subsoiling are shown in Fig 2.3.

Mole drains are unlined channels formed by pulling a bullet shaped metal rod through the subsoil which creates the channel by localised compaction, and creates wider scale fissuring upwards. The method works well in plastic, cohesive, clay soils. In general a minimum clay content of about 30% is recommended. The ground wetness at the time of mole ploughing is quite important; if the ground is too wet there will not be good fracturing to the surface, if the soil is too dry a stable channel cannot be formed. Well formed

**(a)**




**(b)**

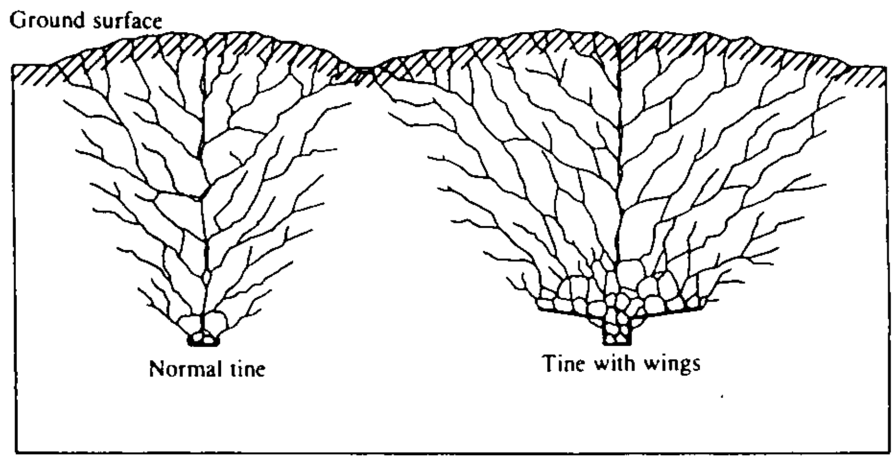



*Figure 2.3 Secondary drainage : (a) mole drainage (b) subsoiling*

mole channels continue to function for, say 2 to 10 years (depending on soil type) before renewal. A depth of 45-60 cm is typical, with spacings of a couple of metres.

Subsoiling is used where there is severe compaction of the upper subsoil, requiring more extensive loosening than can be achieved with a mole plough, or where variable soil texture might cause rapid failure of the mole channels. The extent of loosening may be increased by fitting blades or wings. As the aim is a general shattering of the soil, the fractures from adjacent runs should meet at the surface. As a general rule the spacing should be about 1.5 times the working depth, although this depends on site conditions and the type of subsoiler used. At the time of subsoiling the soil must be sufficiently dry to ensure good friability. As with mole drainage, regular renewal is necessary.

In slowly permeable soils the pipe drain system may be linked to the surface or to the secondary treatment by a permeable fill. This usually comprises gravel or crushed stone and is put into the trench above the pipe instead of replacing the excavated soil. These stones are generally 5-50 mm in size and give a relatively high hydraulic conductivity. A permeable fill surround also improves the flow of water into a pipe drain by reducing the 'entry head loss'. However, the cost of permeable fill is high (it may represent half the cost of some schemes) and so it is not always used.

### 2.4.3 Pipe systems

The traditional pipe material is a clay tile. These have been used since the end of the eighteenth century. Modern tiles are a uniform size, being 30 cm long and with a 75 mm internal diameter. Since their development in the late 1950s plastic pipes have come to increasingly replace the use of clay pipes, being much lighter and more easily handled.

The life expectancy of pipe drains should be at least 10 years, with 30-50 years as typical. Some may continue to function for much longer, and many drains installed in the last century are still working satisfactorily. This depends not so much upon the type of drains but rather on there being a good gradient and few fine silts in the soil, which together help to prevent the drain silting up.

Various methods have been used to estimate the pipe sizes required for a particular scheme. Oversized pipes are uneconomic, whilst if they are too small then the water table may rise to near the surface, damaging the crop. It may also lead to collapse of the mole channels. Possibly the first published measurements of drainflow rates were those of Roe (Beardmore, 1851) who over a six-month period recorded the flow from the single drain outfall of a 33 ha field. The maximum observed flow was about 3 cubic feet per minute per acre (0.57 l/s/ha or 0.21 mm/hr) resulting from 1/2 inch (13 mm) of rain in 1 hr. The time lag between the heaviest rain and greatest flow was between three quarters and one hour.

In choosing the pipe diameter for a particular scheme a number of factors are taken into account. The design rainfall is a major consideration. For normal underdrainage the upper soil layers provide some short term storage capacity. Since a limited period of waterlogging is not crucial to most crops in winter, drain design is usually based on the amount of rain likely over 5 days at a given return period. This depends on the crop type and ranges from 1 year in 1 for grassland to 1 year in 5 for root crops and up to 1 year in 10 for horticultural crops. In recognition that it is unwise for mole channels to be full of water for a prolonged time, the design rain duration is reduced to 1 day, for the same return period, for mole drained schemes. Rainfall statistics are based on records collected by the UK Meteorological Office, and tables have been prepared for agricultural use (Smith and Trafford, 1976; Castle *et al.,* 1984).

The design rainfall value is multiplied by a 'drainflow factor' to give the design flow. This factor varies from 0.4 to 1.0 (MAFF, 1982) and depends on three aspects. It increases for : (a) more permeable soils (b) flatter sites (c) intensity of land use and cultivation - greater for arable than grass, and for pipes with moling than for pipes alone. Combining these unit area flows with the area to be drained by each pipe yields the required pipe capacity. The pipe size required can then be read from standard design charts for a given gradient and a given pipe material (hydraulic roughness). To allow for any progressive reduction in discharge capacity due to sedimentation in the pipes an additional 10% is often made to the design flow (Castle *et al.,* 1984).

Such an approach ignores the normal hydrograph shape of storm runoff response and assumes instead a steady flow over 1 or 5 days. Peak flows will be much greater than this average value. This will tend to dampen the peak response. It is more likely to limit peak flows in modern plastic pipe systems than traditional clay pipes since the latter had a minimum diameter of 75 mm which is much larger than the design capacity of most laterals and minor drains (Trafford, 1973b; Castle *et al.,* 1984). Plastic pipes in contrast come in a much wider range of sizes, down to 50 mm (Bailey, 1978). Most drainage pipes installed in Britain in this and the last century comprised clay tiles. Plastic pipes only started to become popular in the 1970s. In England and Wales their use increased from only 4% of schemes in 1971 to 34% in 1980 (Armstrong, 1981) and currently they account for about 80% of drainage work. In Scotland the picture is similar; currently about 70% of field drainage uses plastic pipes (Robinson *et al.,* 1990).

The collection of data on drainflow rates has led to an awareness of the problems when pipes run under pressure (surcharging), and to an increase in design flow capacities. Similarly, the more frequent use of secondary treatments, with larger drainflow factors and a short design rain duration (but greater intensity) has also led to increasing design capacities. This in turn results in increasing peak outflow rates. The change to plastic pipes, which are manufactured in different sizes, means that there is a greater need for better pipe design criteria.

## 2.5 GEOGRAPHICAL DISTRIBUTION OF FIELD DRAINAGE

In addition to the national statistics on field drainage, regional information has been compiled by counties or groups of counties (Green, 1973; 1979b).

Data for England and Wales were published by MAFF Divisional Areas after 1950 and by counties from 1963. These data provide the opportunity to look at broad regional patterns, but are much too coarse to provide information on the extent of drainage in a particular river basin. For this study, more detailed information was sought.

### 2.5.1 Data sources

In the 1970s it was thought useful by MAFF that detailed information on field drainage should be collected to enable better guidance to be given on drainage system design. This information was compiled by government drainage advisors as part of their grant aid procedures. Data were produced for each civil parish. Since there are nearly 12,000 parishes in England and Wales and 900 in Scotland this provides a much more detailed source of spatial information than the county totals. The data were collected and stored separately by different organisations in Scotland (DAFS) and England and Wales (MAFF). As a consequence it was necessary to obtain the drainage data from both sources.

Before a drainage scheme in England and Wales could qualify for grant aid, prior approval was required. In the majority of cases this involved a site visit by a government drainage advisor to the proposed scheme. The drainage officer advised on the layout of the new scheme and recorded a number of features of the site. In England and Wales from 1971-80 a considerable amount of technical information was recorded on standard forms and subsequently input to a central MAFF computer. A number of automatic checks were made to ensure that the values lay within reasonable limits, and in cases where they did not, the scheme details were returned to the local drainage advisor for verification and resubmission.

Summaries of subsets of these data have been published (Green, 1976; Armstrong, 1978, 1981), but this study entailed the first comprehensive analysis of the geographical extent of field drainage. Since the collection of drainage statistics ended in 1981, this 10-year period of detailed information (1971-80) provides a unique opportunity to examine the spatial patterns of drainage activity and techniques. Furthermore, since this decade corresponded to the period of maximum drainage activity, the data represent almost half of the two million ha drained in England and Wales this century.

These data, relating to over 100,000 drainage schemes, comprising about 8,500 $km^2$ of farmland, were transferred on magnetic tape to the Institute of Hydrology where all the analyses subsequently described were performed. The MAFF only had four digit grid references for the parishes, indicating the 100 $km^2$ block in which the centroid lay, but more accurate locational information was required for this study. Full 8 digit grid references for the centroids of all the parishes were obtained in manuscript form from the Ordnance Survey and added to the parish drainage database.

The drainage data were then subject to further checking. A major problem was discovered relating to the MAFF parish numbering system, based on the county and parish. Implementation of the 1972 Local Government Act led to the reformation of local government in England and Wales with effect from

1st April 1974. This was part-way through the study period, and resulted in a large number of anomalies due to the continued use by some MAFF personnel of the old county parish reference codes. Subsequent revision of the new county boundary between West and North Yorkshire resulted in further changes. These incorrect reference codes had to be identified and manually corrected to provide a consistent data set prior to analysis. This was a considerable task, but was successfully completed except for a few schemes where the parish reference codes had been miscoded and these invalid numbers had to be rejected from the analyses.

The only locational information for each drainage scheme is the parish containing the registered farm office, rather than the parish(es) containing the farmland. This presents a limitation to the spatial resolution that may be obtained and there are known to be some instances where the land being drained was in a different parish to the farm office. However, in a regional study of the parish drainage totals for Berkshire, Buckinghamshire and Oxfordshire, Green (1975) found a close relationship between drainage activity and the spatial distribution of soils and geology. With about 12,000 parishes in England and Wales, and a median size of 7 $km^2$ these data are much more detailed than any previously available, and were felt to be sufficiently adequate for mapping national and regional patterns. In the case of very small areas, large scale maps held at local MAFF offices would be necessary. This local approach is only feasible for limited areas and is described for a few catchments in Chapter 6.

In Scotland, it was not until 1983 that a systematic survey of grant-supported drainage work was introduced by the Department's agricultural staff. These data were put onto computer, enabling scheme details that had been recorded by civil parish to be made available for study.

The information collected by DAFS for each year from 1983 to 1986 inclusive gave details of approximately 17,000 individual drainage schemes for which a grant had been paid, amounting to a total area of about 40,000 hectares (400 $km^2$). For each scheme a drainage information sheet was completed by DAFS staff, who are qualified agriculturalists and have had further training in the theory and practice of land drainage and in assessing the physical properties of soils. These forms were filled in at the time that claims for grant were certified, and so record what actually occurred in the field. The great majority of drainage schemes receive grant aid, and works carried out without grant (and so not recorded) are believed to be low. More recently with falling levels of grant aid for drainage activity these statistics became less reliable, and the gathering of this survey information was discontinued in December 1988. This period since 1983 therefore represents a unique record of drainage information for Scotland. The records for each scheme include the area of land improved, the type of system and the cause of poor natural drainage.

Computerised records of the size and location of the civil parishes in Scotland were not available from DAFS. Data on the total land area of each parish were obtained from the Department of Geography at the University of Edinburgh. The frequency distribution of rural parish areas is positively skewed with a median value of 47.5 $km^2$ and a mean of 90 $km^2$. The centroid of each parish was obtained using a map at 1 : 625,000 scale of parish boundaries produced by DAFS. Both sets of data were then manually input to the computer at the Institute of Hydrology for the analyses.

Once the parish data from MAFF and DAFS had been checked they were ready for analysis and mapping. Computer plotting was used to avoid subjectivity and achieve consistency by interfacing the drainage database with the SURFACE II gridding and contouring package (Sampson, 1978). The first step in generating the maps was to interpolate drainage information from the irregularly spaced parish centroids to a regular grid. A 5 km by 5 km sized grid was selected, and has been used in other agricultural mapping studies (Coppock, 1976a). The techniques used are described in detail by Sampson (1978) and involved fitting a first order trend surface to the nearest four parish data points and then taking a distance weighted average of the projected surfaces at the grid node. The resulting grid points were then subject to a single arithmetic smoothing to eliminate very small scale variability. A number of grids were generated using different combinations of interpolation and smoothing parameters in order to choose the one which provided the best combination of clarity and detail. Once the regular grid of values had been derived, linear interpolation was used to contour the data. The results were first drawn by computer plotter and then the maps were redrawn and shading added for clarity.

## 2.5.2 England and Wales

About one million ha were drained in the decade 1971-80. This was about 10% of the agricultural land of England and Wales, and equivalent to the total drainage in the previous three decades. Figure 2.4 shows the percentage of the agricultural area drained during the period 1971-80, and demonstrates that the majority of field drainage has taken place in the south and east. A broadly similar pattern was identified by Green (1973) for drainage in the 1950s and 1960s using county totals.

This concentration of drainage activity in the lower rainfall areas of the country is at first suprising, but in fact expresses the difference in farming systems. As a gross generalization, the north and south west are predominantly grassland, and the south and east are arable land dominated by cereal production (Coppock, 1976a; Bailey, 1978). The heavy and frequent rain in the north and west does not favour tillage crops (cereals and root crops); the wet conditions are unsuitable for operations such as seedbed preparation, sowing, fertilizer application and harvesting. In contrast, the lower rainfall in the south and east is sufficient for tillage crops, and crop operations benefit from the smaller number of rain days. These areas also benefit from from higher temperatures and longer growing seasons. In broad terms, tillage crops are mainly found in areas with under 750 mm rainfall per year. The lower rainfall is less well suited to grass production which requires adequate water in the summer growing season. Grass does well on the heavy soils of the midlands and south. The wetter north and west are not ideal for good quality grass, but are even less suitable for tillage.

The rate of drainage work has been much lower for grassland than in arable areas. In grassland farming for milk or meat production cash flows are much smaller than in arable farming and much of the capital is tied up in livestock and buildings. Furthermore, although much grassland might benefit from

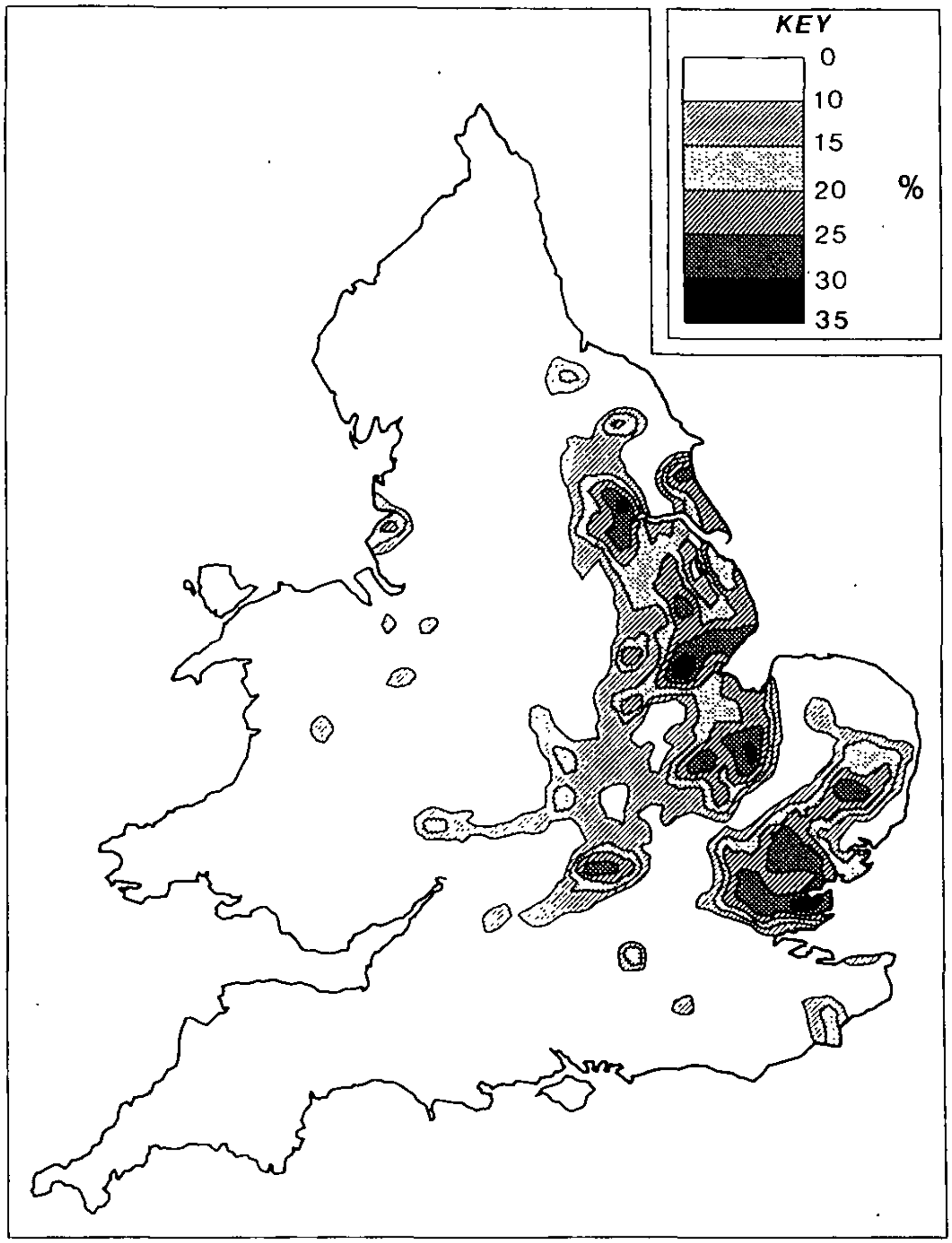



*Figure 2.4 Percentage of agricultural land in England and Wales underdrained in the period 1971-80*

drainage, the farmers may not have the facilities to make use of the extra grass (Forbes *et al.*, 1980). As a result, there is often neither the incentive to invest in grassland drainage, nor the ability to pay for it, despite the higher rates of grant paid in the less favoured hill areas. Where drainage of grassland has taken place it has generally been in areas where intensive dairy farming predominates. This is mainly in Cheshire, Shropshire, Staffordshire and Somerset.

On the arable lands of eastern England farmers find that autumn access onto the land is vital for the cultivation of autumn cereals. The economic differential between autumn and spring sown cereals is so great that drainage to extend the working period has become an essential part of continuous arable cultivation, wherever wetness is a limiting factor. As a result, there has been a concentration of drainage activities in the London clay area of Essex and the boulder clay plateau of East Anglia. A similar belt of high drainage activity runs through Lincolnshire, with an offshoot into the upper Thames basin of Oxfordshire. Apart from the chalk lands, there is thus a rough correspondence between the areas of high drainage activity and the cereal lands.

An exception to this general pattern is the concentration of drainage activity in the silt and peat lands of the Fens of East Anglia where an intensive production system depends totally on artificial drainage. Many of the crops are of extremely high values, and sensitive to even short periods of waterlogging; in these circumstances 'insurance' drainage is often installed. This drainage also enables the harvesting of many horticultural crops late in the winter period. A similar explanation also applies to the coastal plain of Lancashire where there is a local concentration of horticulture.

Field drainage tends to be associated with a change to a more intensive farming system (Fig. 2.5). Thus in grassland areas there is a general change

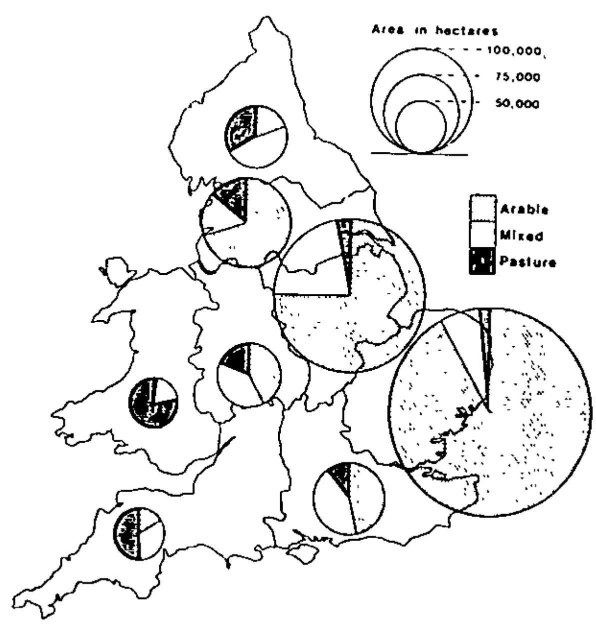



***Figure 2.5 Land use after drainage, 1971-80, in England and Wales. Data based on MAFF regions (Armstrong, 1980)***

to more intensive dairying and mixed farming, whilst in the arable areas the drainage is intended to assure and increase yields. Approximately equal areas of grass and arable land were drained, 1971-80, but only about one quarter remained under grass afterwards.

*Drainage problem*

Each drainage scheme in England and Wales was classified according to the drainage problem which it was intended to remedy. This classification was based on the source of the water - surface water, groundwater or spring water (Table 2.1). In practice these categories are not always mutually exclusive, and the problem recorded was the one that the Drainage Officer considered to be the most important. Consequently there is an element of subjectivity in some of the assessments. Robinson and Armstrong (1988) identified some features in the data for England and Wales that could be related to the preferences of individual Drainage Officers in classifying complex situations. The same problem was encountered in an earlier drainage survey in southern Ireland, where the solution adopted was to discuss apparently anomalous data with the District Officers responsible, to resolve conflicting opinions (Galvin, 1969, 1971).

*Table 2.1 Cause of drainage problem (% drained land, 1971-80)*

| | |
|---|---|
| Surface water | 58% |
| Groundwater | 34% |
| Spring water | 8% |

A separate map was produced of the percentage of drained land falling into each category. These were checked in two ways. Firstly, the maps were compared and found to fit together well; high values on one being matched by low values in the others. For individual areas the values added up to approximately 100%, confirming that the gridding and smoothing of the data had not distorted their patterns excessively. Secondly, the maps were discussed with experts in MAFF, associated with the data collection exercise, who verified the patterns found and indicated that idiosyncratic reporting had only a restricted and generally unimportant effect on the results.

The main types of drainage problem being tackled in England and Wales are summarised in Fig. 2.6 for all areas with over 10% of land drained in the period 1971-80. It must be emphasised that this, and subsequent maps, refer to the features of those drained areas. Thus, for example, in interpreting the drainage problem map it must be borne in mind that there are many areas with naturally permeable soils which do not require artificial drainage. Detailed information about soils and their properties are given in SSEW (1983) and reference to individual soil series in Clayden and Hollis (1984).

Drainage to alleviate surface water occurs widely throughout England and Wales, whilst the other types of drainage are more localised. Thus, drainage for groundwater control is mostly found in eastern England for permeable soils in basin situations; especially in the Fens. Spring water drainage is largely restricted to upland areas in Wales and the south west.

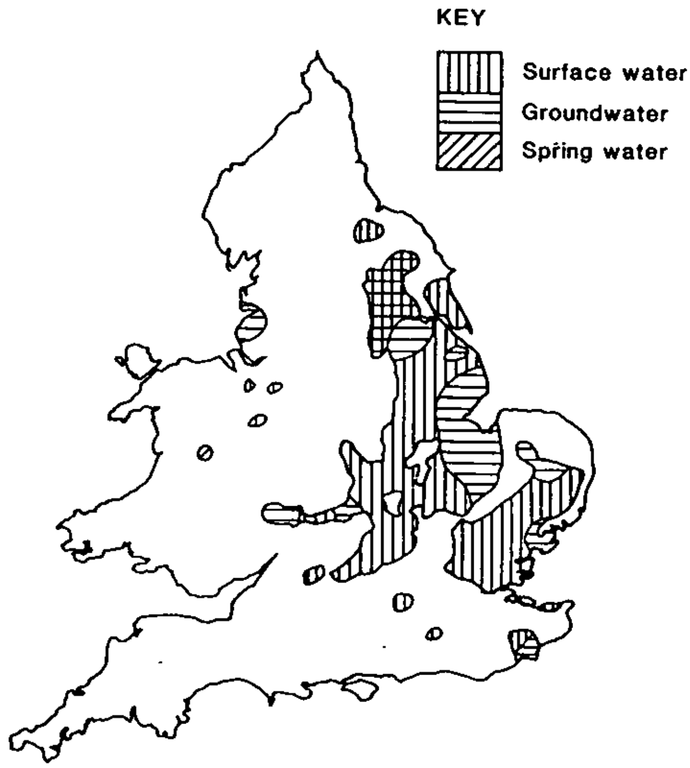



*Figure 2.6 Predominant type of drainage problem tackled in those areas with more than 10% field drainage, 1971-80*

*Types of underdrainage systems*

The use of a secondary treatment in drainage schemes was also recorded (Table 2.2) and was found to have been adopted in 57% of the drained areas. In addition a further 5% is estimated to have had secondary treatment which was not eligible for grant aid, and so not recorded in the statistics. Overall then, over 60% of all schemes used moling or subsoiling. Moling tends to be concentrated in the south and east, due partly to the need for an adequate soil moisture deficit for successful mole channel formation and the heavy clay soils developed from boulder clays and the London clay. Subsoiling extends around the 'core' mole drainage area and is particularly important in the Midlands and Yorkshire. It is thus used in areas where a secondary treatment is needed but mole drainage is a doubtful option due to soil variability. In practice, the distinction between mole drainage and subsoiling is not always clear (Trafford, 1975). Much subsoiling is done below the critical depth, and thereby leaves a channel behind, although less stable and of shorter life than a conventional mole channel. Similarly, mole drainage is often accompanied by a considerable amount of shatter.

*Table 2.2 Use of secondary treatment in drainage schemes (% drained land, 1971-80)*

| | |
|---|---|
| Moling | 32% |
| Subsoiling | 25% |

### *Old drains*

Information on the presence of old drains was routinely collected by drainage advisors on their visits to farmland where an application had been made for grant-aid for drainage work. Grant-aid was only available to replace drains installed prior to 1939; since there was very little drainage in the early part of this century these are likely to be nineteenth-century drains. These are very different in appearance to modern drainage pipes, being of different sizes and shapes and often poorly extruded. Although it is not generally possible to date old pipes, those stamped with the word 'DRAIN' were almost certainly made between 1826 and 1850 (field drains made in this period were exempt from a tax on clayware materials if marked in this manner).

By assuming that the areas visited in response to farmers' requests for grant-aid for drainage work constitute a 'random' sample of farmland in a given parish a broad estimate may be made of the percentage of land that contains nineteenth century drains (Green, 1980; Robinson, 1986a). It must be recognised that whilst such an assumption may be reasonable for parishes that are homogeneous in soils and topography, it is likely to be less realistic in others where only part of the parish is suitable for drainage. If significant areas of a parish had good natural drainage (e.g. chalk) or were uneconomic to pipe drain (e.g. steep, rocky and isolated moorlands), then the redrainage of small areas of better quality valley bottom lands would give rise to an overestimate of the total amount of old drains in the parish. On the other hand, underestimates would result for those parishes where many old drainage systems still functioned satisfactorily, as these fields would not be visited and so not included in the data collection. Similarly, many old drains were probably not found, particularly in areas where they had been installed by followers of the school of 'deep drains'. These and other potential sources of inaccuracies of this approach to estimate the extent of old drains are summarised in Table 2.3.

Whilst acknowledging that this approach is far from ideal, two factors must be borne in mind. Firstly, the potential errors are both negative and positive, and to some extent, therefore, will be self-cancelling. Secondly, there are serious problems with the other estimates of nineteenth-century drainage outlined in Section 2.3; the contemporary estimates have been shown to be unreliable and conflicting. The present method provides an entirely independent approach to the problem.

Summing the areas drained for each parish yields a value of 57,000 $km^2$ having old drains. This represents 52% of the agricultural land in England and Wales. Given the uncertainties and assumptions of the two approaches this is remarkably similar to the estimate of 50,000 $km^2$ obtained by Trafford (1970) from records of clay pipe production. These two independent estimates, taken

*Table 2.3 Possible sources of uncertainties in using the parish data to estimate the extent of nineteenth-century drainage*

(a) Overestimates:

- Unrepresentative sample of land within parish inspected, other areas might not require drainage (now or in the past)

- Only a part of a field inspected might contain old drains, but the whole field is recorded as having old drains

(b) Underestimates:

- Unrepresentative sample of land, other areas might contain old drains which are still functioning adequately

- The site might contain old drains, but they were not detected and so went unrecorded

together with Belding's (1971) figure of 21,000 km$^2$ having still-functioning nineteenth-century drains, indicates that the extent of underdrainage in the mid- to late- nineteenth-century period of 'High Farming' was very much greater than contemporaries such as Denton and Caird realised. This represents an enormous achievement by the agricultural community, and one which must have been largely financed by private loans or from the landowners' own resources, and so have gone largely unrecorded in historical sources. The extent of this effort may be judged by comparison with the amount of drainage in the present century. Even if the lower figure of 50,000 km$^2$ is used for the nineteenth-century drainage, this is still two and a half times the 20,000 km$^2$ drained between 1940 and 1981. Figures for pipe production confirm the difference between the two centuries; annual production in the mid- nineteenth century was about four times that in the 1970s. Allowing for closer drain spacings than those used at present, this represented an average rate, 1840-90, of about 80,000 ha per year (Trafford, 1970). This rate was only reached again in the 1970s.

These data can also be used to study the regional variations in nineteenth-century drainage in England and Wales, although it must be recognised that the figures will become less reliable as smaller areas are considered (Fig 2.7).

The pattern of drainage shows a good general agreement with the spatial pattern of soils based on their hydrological properties (e.g. Farquharson *et al.*, 1978). Areas of low drainage activity can be readily identified with areas of permeable soils having good natural drainage (e.g. the North and South Downs, Cotswolds and Chilterns in southern England, and the Yorkshire Wolds in northern England). Higher rates of drainage activity occur in areas with more impermeable soils, such as the clay soils of Essex, Suffolk and Lincolnshire, and the Weald in Surrey and Sussex. The highest rates are found in the north and west where there is high rainfall and the soils are low permeability peats and heavy clays. Thus it seems that in contrast to the pattern of drainage in this century, which is dominated by economic factors, in the nineteenth century field drainage activity was controlled by environmental factors.

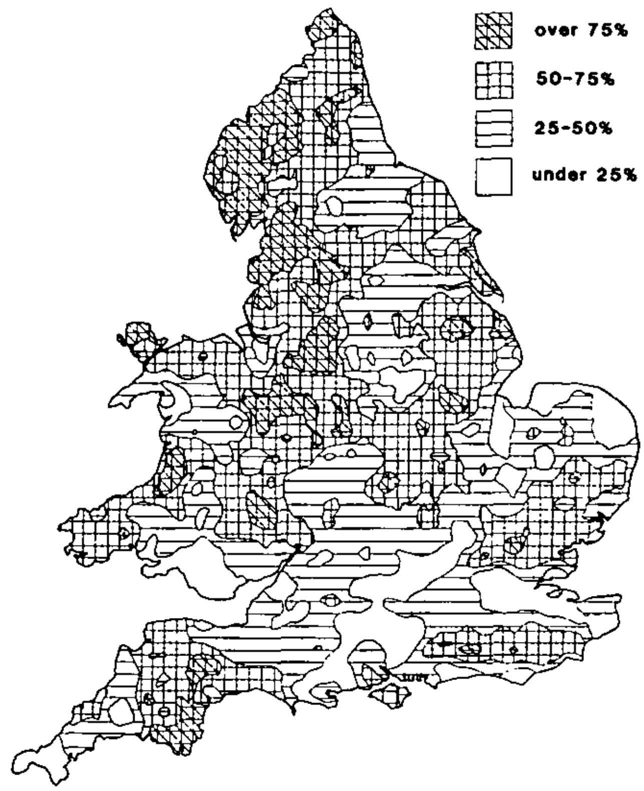



***Figure 2.7 Percentage of agricultural land inspected 1971-80, which was found to contain nineteenth-century field drains***

The conclusion that in the nineteenth century drainage activity was greatest in the wetter north and west of the country is also supported by some agricultural historians. Sturgess (1966, 1967) has argued that drainage was concentrated on clay soils in the north and west since agricultural production there could only be increased with artificial drainage to prevent the waterlogging of crops in winter. This drainage took place at a time when the price of corn (the traditional clayland crop) was low, and was often associated with a change to grass, mostly for cattle production. On the lowland clays in eastern England, the smaller rainfall limited the growth of grass in summer and made the investment in drainage a less economic prospect than in the wetter and more productive grass growing areas of the west and north.

The overall pattern of nineteenth-century drainage provided by the parish data appears reasonable when compared to what is known about farming practices at that time, but it is perhaps questionable that such high percentages of the land were drained in upland areas such as Cumbria and northern Lancashire, where the economic return on the investment would have been poor. Further investigation indicates that in such areas underdraining was likely to have been concentrated on the enclosed 'in-bye' fields in the valleys, with the open hill lands remaining undrained (both now and in the last century). The occurrence of old drains in such areas would thus reflect these more fertile valley bottom lands, and provide an overestimate of the percentage of the total land. It is difficult to determine the magnitude of such an overestimation, but some indication may be obtained by comparison with the regional survey of Belding (1971) which was based on a random sample of land. The category of land identified as still relying on nineteenth-century drains provides a minimum estimate of the percentage of land with old drains (schemes that had failed would be included in other categories). This yields values of about 10% in southern England and Wales rising to about 35% of the land in northern England, and confirms that higher rates of drainage took place in the latter areas. If only half of the last century's drainage schemes are still functioning, this would give values of about 20% of the land in southern England and 70% in northern England. These figures are thus broadly in agreement with Fig 2.7, although they do suggest, as indicated above, that the parish data resulted in a systematic overestimation for some hill areas.

### 2.5.3 Scotland

The spatial pattern of field drainage shows a clear concentration of work on the lower lying regions of eastern and southern Scotland, and the Midland Valley (Fig. 2.8). This corresponds closely with the distribution of better capability land (Bibby *et al.,* 1982; Soil Survey of Scotland, 1982). This land is predominately used for crops and grass. The main crops are cereals (particularly barley, oats and wheat) and root crops (turnips, swedes and potatoes). Permanent grass is widespread in the lowlands particularly in the south-west. Most of the grass is associated with farms which aim to be self-contained in terms of winter fodder so that a considerable proportion is shut-off from grazing each year to be cut for hay or silage. In areas like north-east Scotland barley and turnips are also grown for winter fodder. The pattern of Scottish agriculture is described in detail elsewhere (Coppock, 1976b, Clapperton, 1983).

Much of this better quality land has already been drained at some time in the past (Green, 1979a) and the current drainage operations are largely concerned with the re-drainage of land. Thus the areal pattern of land drainage is basically constant over time and is very similar to the distribution of better land. The pattern of drainage revealed in these maps for data 1983-6 is consequently broadly representative of a much longer period than the four year sample period would at first suggest.

***Drainage problem***

In the Scottish data set the reason that artificial drainage was required at a site was attributed to one of four possible causes of poor natural drainage: perched water table, high groundwater table, spring water or surface inflow. (Table 2.4). The first three categories are self-explanatory and correspond to those used in England and Wales but the fourth, surface inflow, requires explanation. Surface inflow comprises the control of surface water entering a field from nearby higher land. This usually requires a cut-off drain or ditch to intercept the water rather than underdrainage of the field. It is recorded in a separate category since the 'area to benefit' is often quite large and difficult to define, and the reason for drainage is external to the site characteristics of the field benefitting from the drainage. It is important in areas where most of the productive land is situated in steep-sided valleys; inflow from nearby steeply sloping land, often moorland, cannot be effectively controlled by drainage of the source area as it would be in an all-arable district.

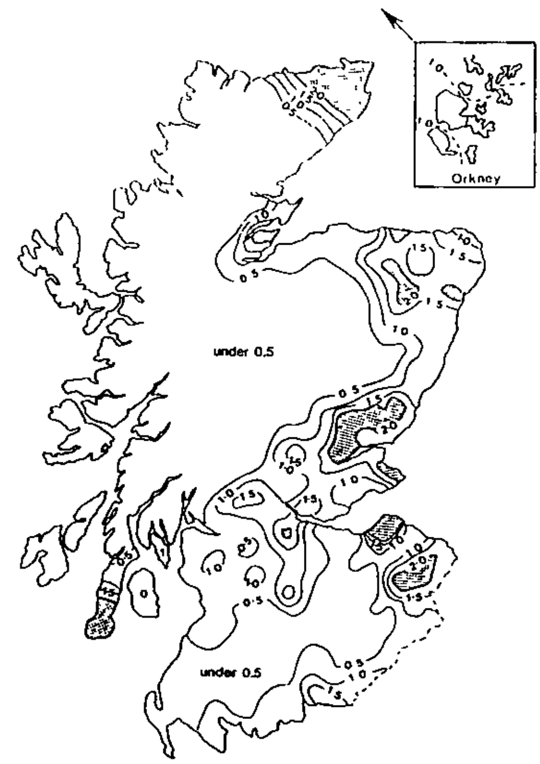



*Figure 2.8 Percentage of agricultural land in Scotland underdrained in the period 1983-6*

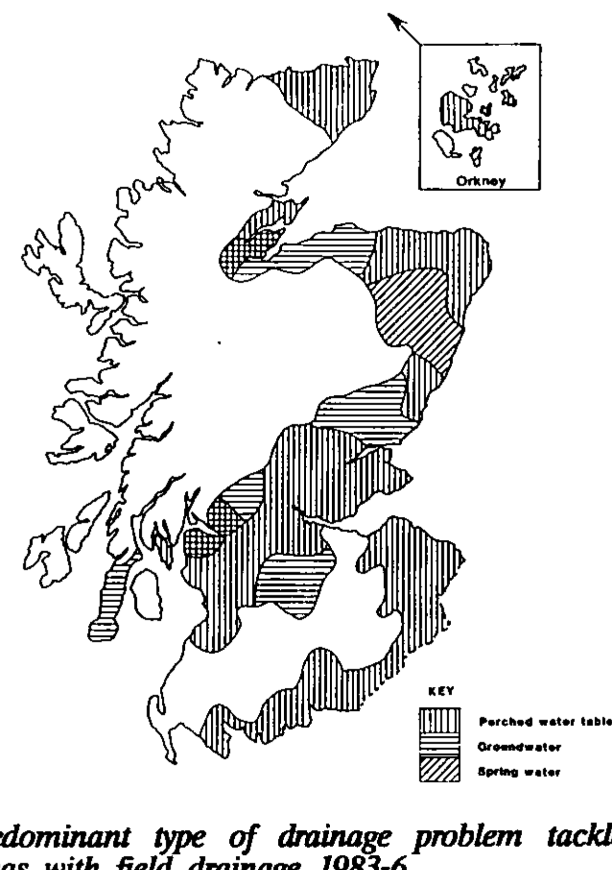



*Figure 2.9 Predominant type of drainage problem tackled in those areas with field drainage 1983-6*

*Table 2.4 Cause of drainage problem (% drained land, 1983-6)*

| | |
|---|---|
| Perched water table | 41.1 |
| Ground water | 15.6 |
| Spring water | 9.5 |
| Surface inflow | 33.5 |

The distribution of the main types of in-field drainage problem for the schemes tackled in 1983-6 is mapped in Figure 2.9 showing (1) perched water (2) groundwater and (3) spring water. Where two types of problem were co-dominant they are shown over-shaded. For clarity only those areas where at least 0.5% of the land was drained in this period are shown.

As with the corresponding map of drainage problems in England and Wales (Fig. 2.4) this map only deals with those areas drained, and should not be confused with the general pattern of soil water regimes over the country. The latter is described in Soil Survey of Scotland (1982). The greater part of Lowland Scotland has impermeable glacial tills on which soils tend to be affected by a perched water table; excess rainfall cannot percolate downwards through the subsoil. Impermeable soils are found mostly in the East Perthshire/Angus areas and to a lesser extent in Fife, East Lothian and Berwickshire. The concentration of artesian springs in Aberdeenshire is caused by the peculiarities of differential patterns of glacial erosion and deposition (Henderson, 1973).

*Types of underdrainage systems*

Technical aspects of each drainage scheme, recorded by DAFS, included the type of pipe material used, the spacing between pipes, whether or not the scheme used permeable fill over the drains, and if the ground had a secondary treatment (subsoiling or moling) to improve soil permeability. In contrast to England and Wales, secondary treatment is not common in Scotland, with only 10% of drainage work recorded as including subsoiling, and no mole drainage at all (Table 2.5). It should be borne in mind, however, that subsoiling does not always go ahead when underdrainage is installed and when it does proceed since it is much cheaper than the pipe drains there is not always a claim for grant. Hence it would not be recorded.

*Table 2.5 Type of drainage system (% of land drained, 1983-6)*

| | |
|---|---|
| Pipe material : | |
| Plastic pipes | 69.0 |
| Clay pipes | 28.0 |
| Other | 3.0 |
| Permeable fill | 51.0 |
| Secondary treatment : | |
| Subsoiling | 10.1 |
| Moling | 0.0 |
| None | 89.9 |

Subsoiling reflects both the crop type and soil properties. Its adoption tends to be associated with arable crops, especially root and vegetable crops, but also for cereals in areas where their root development would be inhibited by the formation of a soil pan. There is a general belief that Scottish soils are not suitable for mole drainage as the clay content is too low for mole channels to be formed. The limited amount of secondary treatment is more a reflection of climatic constraints, restricting the period within the year when it may be carried out, rather than restrictions due to soil type. To subsoil effectively, the soil must be fairly dry, e.g. in the wetter west the higher rainfall means that the fine textured soils rarely dry enough but the same soil type on the east will probably be sufficiently dry most years. Due to the very small number of schemes using subsoiling the mapped distribution is not reproduced here, but it does show a tendency for greater (albeit limited) activity in southern and eastern parts of Scotland.

The records (Table 2.5) show that in 1983-6 plastic pipes were used on 69% of the area drained, while clay pipes were used on 28%. The remaining 3% of the drained land had pipes of some undisclosed material, usually concrete pipes. There has been a steady increase over time in the use of plastic pipes which accounted for about 50-60% of drainage in the mid 1970s. Plastic pipes are the preferred type of drainage material particularly in upland areas due to their much lower transport costs. They are also cheaper and easier to install. Two notable exceptions to this trend are the north-east region, especially north of Aberdeen where a local source of clay tiles is competitively priced and the short pipe lengths are particularly suitable for deep drainage trenches associated with interception of spring seepage, and in East Fife where land drainage contracting is dominated by a single business, the proprietor of which has a resolute belief in the benefits of clay tiles (Robinson *et al.* 1990).

About half the land drained in this period had a permeable gravel backfill. This is put into the trench above the pipe drain to provide an easy route for the water down from the ground surface. There was a complex spatial pattern in the occurrence of permeable fill with it being used in most schemes in Caithness, Angus, East Lothian and northern Ayrshire, but little used in the North-east and Fife.

A limited drainage survey carried out in the early 1970s by a working party set up under DAFS, concluded that there was no simple relationship between lateral spacing and land use, soil series or rainfall (Mackay *et al.*, 1973). Differences occurred between schemes on similar soils, and, conversely, the same drainage methods were employed on different soils. It appeared that local tradition played a large part in determining which method should be adopted, and that often there was very little exchange of ideas between neighbouring areas. The survey of drainage schemes described here was initiated to monitor this very point and results tend to show that traditional local preferences have not diminished significantly.

***Old drains***

As in England and Wales, much drainage in Scotland is concerned with the replacement of old drains. They were not recorded as part of the drainage survey, so it was not possible to carry out a similar analysis to that for England and Wales (Section 2.5.2). Old drains were, however, recorded in earlier more general, grant-aid records but are only available in summary form as regional totals. These show a greater frequency of old drains in the eastern regions (North East, East and Lothians and Borders) which are similar to the areas being drained in recent years. This suggests that the areal distribution of underdrainage in Scotland has been much more constant over time than that south of the border, and this is probably a reflection of the much more severe restriction on agriculture by climate and soils (Roy and Hough, 1978; SSS, 1982)

## 2.6 HILL DRAINAGE

In moorland areas the installation of expensive pipe systems cannot be justified for the extensive open grazing systems of farming, and the main form of drainage is the cutting of open drains (variously called moorland gripping, sheep drains and hill drains). These are open channels, typically 40-45 cm deep with a tapered width narrowing from about 50-75 cm at the top to 15-25 cm at the bottom. They are generally made using a special 'Cuthbertson' drainage plough which cuts a continuous furrow depositing the spoil in a ridge about 50 cm from the drain edge. The drain spacings are of the order of 20 m, but vary widely. Depending upon the site conditions the layout of drains may be herringbone, along the contour or random. Moorland gripping is carried out for sheep grazing and grouse moors. It is assumed to improve the growth and cover of heather and increase the productivity of livestock and grouse.

Although grant aid is given to these schemes, due to their low economic value much less attention has been given by the government's agricultural agencies to collecting reliable statistics. There are no national figures for England and Wales, but in Scotland, where hill land is relatively more important, national and regional statistics have been collected. National figures for Scotland have been published by DAFS (Mackay *et al.*, 1973) and elsewhere (Thompson, 1948; Green, 1974). These indicate that in Scotland alone, nearly 1.8 Mha of moorland were drained in the period 1921-81. These records show even larger year to year fluctuations than those already noted for the areas underdrained, and similarly there must be doubts about the reliability of some of the data. Again, the reason is not clear. Records are believed to be more reliable in recent years, and the spatial distribution of hill drainage is shown for DAFS regions in Fig 2.10. Not suprisingly this map is broadly the converse of the map of pipe drainage.

Equivalent summary data are not available for England and Wales, and it has been widely accepted by researchers that 'Drainage statistics for hill land are not recorded in England and Wales' (Stewart and Lance, 1983; Hudson, 1984). This is in fact not correct; grant-aid records of all drainage work (including hill drains) have been kept at the local offices of MAFF. These are used, for example, to ensure that grant aid is not given twice for drainage of the same area. The existence of these data has not been generally made known outside of MAFF due to its policy of farmer 'confidentiality'. It is considered important that it should not be possible for people other than MAFF staff to know which individual farmers have received state money in grant aid (for drainage or any other purpose).

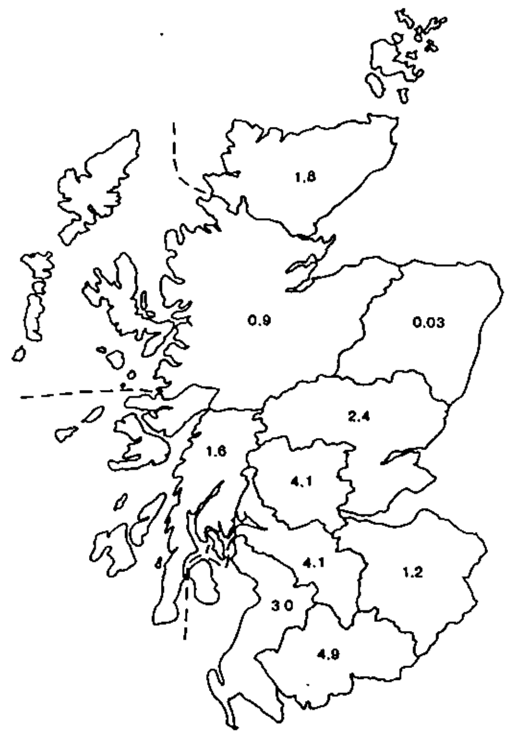



*Figure 2.10 Percentage of land having hill drainage 1972/3 to 1982/3, (based on DAFS regions)*

For this project it was clearly desirable that an attempt should be made to assess the extent of this type of drainage, especially since it has so often been associated with claims of increased flooding in areas downstream (eg Learmonth, 1950; Stewart, 1963; Oldfield, 1983). Since the investigation was undertaken for the MAFF, its normal 'confidentiality constraints' were lifted, on condition that the results should be presented in a form in which individual farms were not identified. Due to the large amount of work involved in abstracting these data from manuscript records held at a multitude of local offices, such a study could only be undertaken for a limited part of the country. The region chosen was the Yorkshire area covered by the Harrogate and Northallerton local offices of MAFF. This includes the River Ouse catchment area in which it was recently claimed that moorland gripping had resulted in flooding at York and Selby (Oldfield, 1983).

The drainage records are kept by MAFF on large scale (1: 10,560 or 1: 25,000) 'master plans' which show the extent and type (pipe or hill drain) of grant-aided drainage. These maps include all schemes since 1939, although records become less reliable in the 1980s with the reduction in agricultural support staff. Each scheme has an individual number which relates to a separate file which contains further details, including the date. Many of these files have been destroyed under the new MAFF policy, but at the time of writing the master plans still survive. Using these maps it was possible to produce Figure 2.11, which is believed to be the first map ever produced of the extent of moorland gripping.

This map shows, not suprisingly, that moorland gripping is concentrated in the upland areas, with low values in the main valleys. An exception to this can be seen in the areas of limestone lithology to the north and west of Skipton The highest rates of moorland activity (>50% of the land) are found in the headwaters of the River Nidd and in Arkengarthdale (a tributary of the River Swale). These are both areas used for grouse shooting which is now a major source of income in many hill areas. Although MAFF grant aid was intended to assist hill farmers rather than shooting estates, the latter have also been able to receive government money due to the fact that they keep sheep on the land at other times of the year. Thus these records include moorland gripping for both types of land use.

Whilst records of the date of many of these drainage works have been discarded by the MAFF, a broad estimate can be made from their reference number, since this indicates the type of grant-aid scheme currently operating when the drainage was approved. Thus, for example, the Farm Capital Grant (FCG) scheme operated from 1971-80 and Farm and Horticulture Development (FHD) scheme from 1974-80. Several grant-aid schemes were usually operating at any one time, and started and ended at different times, so the data give a general rather than a precise picture of changes in rates over time. In assigning the drainage work into periods the following assumption was made: pre-1960 work - all 'D', '20/' and '5/' prefix numbers; 1960s - 'TD' and 'DG' prefixes, 1970s - 'CG', 'FCG' and 'FHD' prefixes, and early 1980s - 'AHG' prefix numbers. The result is plotted in Fig 2.12.

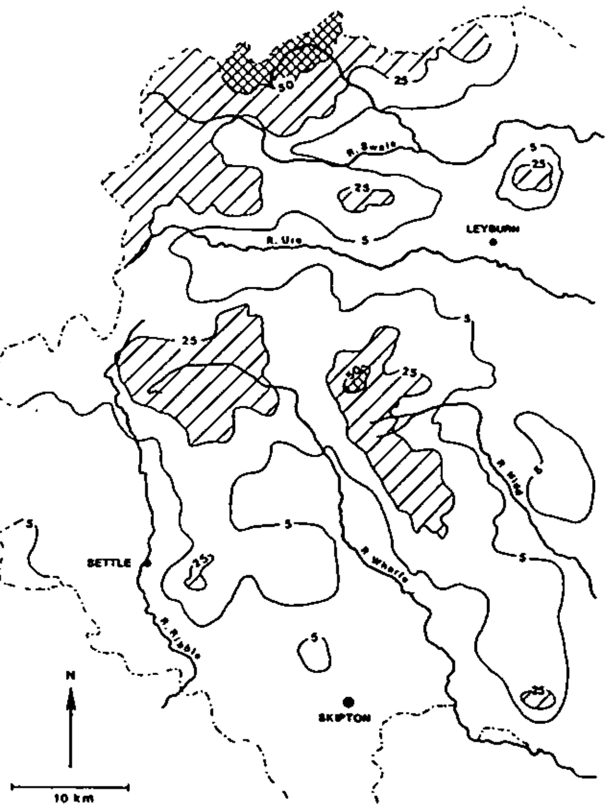



*Figure 2.11 Percentage of land in the western Yorkshire and Pennine region which had moorland gripping, 1940-85*

This indicates that the amount of moorland drainage was rapid in the 1940s and 1950s, declining in the 1960s. Rates then increased in the 1970s and in the early 1980s. There are no comparable data available since then, but there is thought to be only negligible, if any, drainage being carried out at present. This temporal pattern appears reasonable from what is known in general about the upland economy. High drainage activity during and soon after the Second World War was associated with the government's policy of increasing home food production. There was also at about this time the introduction of the Cuthbertson drainage plough which greatly facilitated the drainage of moorlands (Thompson, 1948). Rates declined in the 1960s, but then increased again in the 1970s as part of the general expansion of agriculture. This then declined through the 1980s to the current very low level of activity. The lack of moorland drainage at present reflects both the contraction of agriculture and a change in MAFF policy which now no longer encourages its adoption as it did in the past (e.g. MAFF, 1981). A number of studies have found little evidence that gripping actually improves the vegetation significantly (Stewart and Lance, 1983).

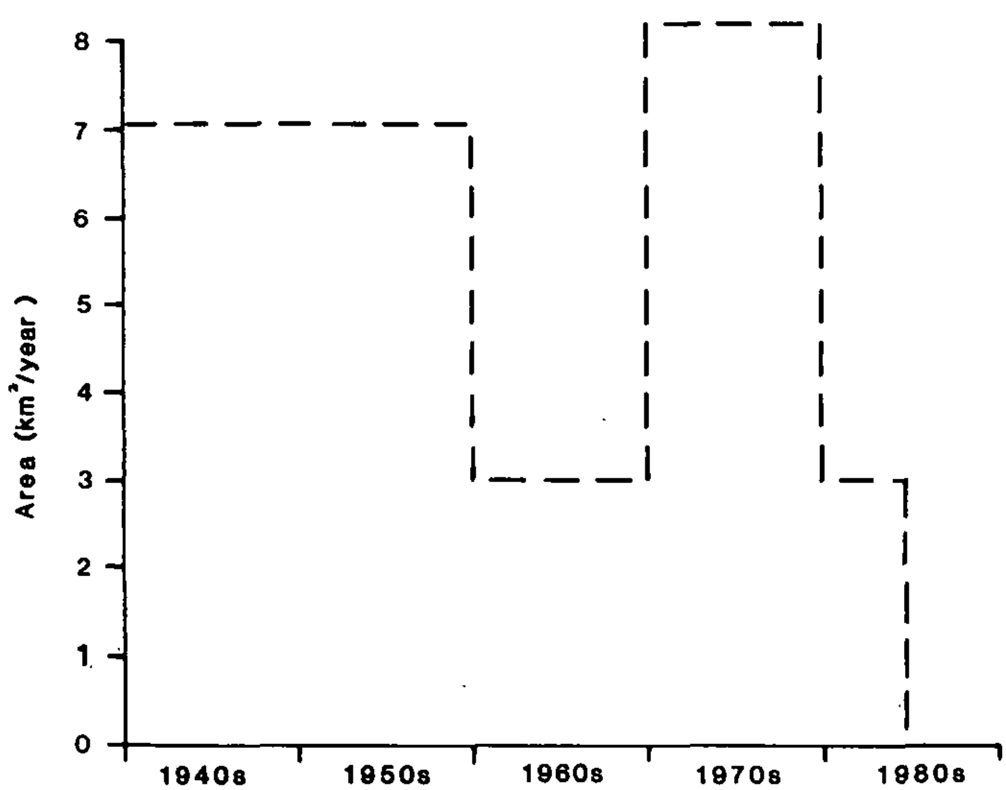



*Figure 2.12 Rate of moorland drainage activity in the Yorkshire study area, 1940-85*

## 2.7 SUMMARY AND CONCLUSIONS

This chapter has summarized the extent and type of drainage activity across Britain, using detailed data collected by government agencies in England and Wales, and Scotland. It was found that the distribution of drainage in recent years reflects mainly economic factors. The highest rates of drainage activity are associated with the predominantly cereal growing areas of the south and east, and the locally important areas of high value horticulture. These areas grow cash crops such as corn, sugar beet and potatoes. There is a high investment in equipment, and the need to maximise economic returns. Artificial drainage both improves crop yields and increases the time during the year when heavy machinery can be used on the land.

These areas have mostly clay soils and as a result over half the drainage carried out was to alleviate a surface water problem. Secondary treatments were used on over half the drained land in England and Wales, but are still uncommon in Scotland. Local tradition continues to have a stronger influence on drainage scheme design than scientific theory.

Evidence is presented that drainage in the nineteenth century, before the collection of reliable records, was even greater than that in the present century and much greater than contemporaries realised. Its distribution reflects the environmental constraints on agriculture. Supporting evidence of the large extent of this drainage comes from the fact that concern was expressed as early as the 1860s that drainage might have an adverse effect on river flows. These fears were reawakened with the second great expansion of agricultural drainage in this century, in the 1970s.

This investigation has identified the most common type of drainage situation as having a surface water problem on a slowly permeable soil; a secondary treatment is frequently used over the pipe drains. These are the site conditions on which most attention should be directed in field studies (Chapters 3 - 5). The location of recent drainage, and hence of streams most likely to provide evidence of altered flow regimes during their period of flow measurements, is greatest in the south and east (Chapters 6 - 8).

# 3. Drainage plot studies

## 3.1 INTRODUCTION

From the discussion of the conflicting opinions given in Chapter 1 it is clear that the collection and analysis of data from case studies is essential. Only then will the current uncertainty be resolved regarding the hydrological effects of field drainage upon the flows into streams and rivers, and the resulting increased (or reduced) risk of flooding to land downstream.

Nevertheless, to date, surprisingly few studies have been carried out on this topic. Although the MAFF have operated field drainage experiments over a number of years these have been run as part of its agricultural advisory service to farmers. Consequently they have primarily been concerned with comparing the effect of different drainage treatments on soil water conditions (and hence crop productivity), and on the 'workability' of the land for heavy agricultural machinery. As noted by Bailey and Bree (1981) such field drainage experiments are mostly of limited use in this debate since usually only flows from the drainage pipes were measured (for information on pipe design capacities) rather than total field outflows (which would also include overland, topsoil and deep seepage flows). Additionally, there were often no measurements of total outflows from a similar, but undrained, 'control' plot.

Those few sites where comparable data of storm period outflows from drained and undrained land were collected by the MAFF have shown conflicting results - drainage resulted in higher peak flows at some sites (e.g. Armstrong, 1984) and reduced peak flows at others (e.g. Arrowsmith, 1983). Thus the impact of drainage might vary between sites due, in some way, to differences in their physical characteristics. These differing results have yet to be explained by the MAFF, it being felt that 'there are so many variable factors in a catchment shape, size, slope, rainfall, soils and geological aspects etc that there might be a range of answers, particularly dependent upon the season of the year' (D. Castle, pers. comm.).

In order to make progress in solving this debate it is clearly desirable to collect data from as many locations as possible, to cover a range of such factors. Then if the effect of drainage appeared to be reasonably consistent for all sites, one would have some degree of confidence that a definitive answer could be given regarding the likely impact of drainage at other similar sites. If, on the other hand, the effect of drainage was variable (as the prolonged nature of the controversy would suggest), either between sites (e.g. differing in slope or soil type) or even at the same site between different storms (e.g. different magnitudes or initial ground wetness), then it might be possible to identify and distinguish situations where drainage may increase or decrease flood risk.

## 3.2 AVAILABLE FIELD DATA

As a first stage, a search was made for experimental sites where comparable flow data had already been collected from drained and undrained land, in order to supplement the few available published studies. Since the results of the MAFF experiments had been published further data were sought from other organisations in the British Isles, including government research institutes and universities. These data had to meet a number of strict criteria for this study :

a) Well defined plot or catchment boundary isolating storm period flows in the study area from the adjoining land, and ensuring the area boundary did not alter over time due to the installation of field drains,

b) Catchments should be small enough to have homogeneous characteristics, and negligible channel routing effects in relation to the within field soil water processes; for this a necessarily arbitrary maximum area of 25 ha was used,

c) No other significant influences during the period of study, other than any intensification of agricultural production that would normally be associated with the installation of field drainage

d) Total plot outflows were measured, and not just the pipe flow or overland flow components,

e) Data from an undrained 'control' catchment - either adjacent, or from the same plot before and after drainage,

f) Good quality rainfall and flow data, and onsite measurement of soil water conditions using either a neutron probe, tensiometers or water table dip wells,

g) Detailed information on the soils, crops and the date and type of drainage carried out. This is essential for interpreting the results in terms of an understanding of the hydrological processes involved, in order to develop the capability to predict the likely downstream impact of drainage at other sites.

### 3.2.1 Selection of study sites

A search was made for possible suitable data by reference to the published literature in scientific journals, to individual scientists and organisations and to surveys of research projects such as the 'Hydrological Research in the United Kingdom' series published by the Institute of Hydrology. After the rejection of some potential study sites which did not meet the above criteria, six sites were considered to be worthy of study and are listed in Table 3.1, together with details of the scientists and organisations responsible for collecting the data and any relevant publications prior to this study. The location of these sites are shown in Figure 3.1 and comprised four sites with mineral soils : (1) Ballinamore and (2) Grendon which both had permanent grassland on a heavy

*Table 3.1 Drainage experiments providing data*

| Site | Main Operator(s) | Previous Publications | Contents/ Conclusions |
|---|---|---|---|
| Ballinamore | W. Burke & J. Mulqueen<br>An Foras Taluntais<br>Dublin | Burke et al (1974) | Water balance |
| Grendon | K. Beven & M. Robinson<br>Institute of Hydrology<br>Wallingford | Beven (1980) | Unpredictable effect on peak flows. |
| Blacklaw | R. A. Robertson & I. A. Nicholson<br>Macaulay Institute<br>Aberdeen | Robertson et al (1968) | Water balance before drainage |
| Staylittle | M. D. Newson<br>Institute of Hydrology<br>Staylittle | - | |
| Tylwch | M. D. Newson<br>Institute of Hydrology<br>Staylittle | - | |
| Withernwick | E. Ryder & R. C. Ward<br>Dept of Geography<br>Hull University | Ryder. (1979) | Mainly instrumentation Base flows increased |

clay soil, (3) Tylwch with a silty clay loam soil and a high annual rainfall, and (4) Withernwick with a lighter clay loam soil under arable farming. Two sites had peat soils : (5) Staylittle with an amorphous peat soil overlying a mineral subsoil, and (6) Blacklaw Moss which had a deep fibrous *sphagnum* peat soil. These individual field studies by various organisations reflected their different concerns, and were predominantly intended for purposes other than the effect of artificial drainage on downstream channel flow regimes. The Ballinamore and Blacklaw Moss sites, for example, were operated by agricultural research organisations whose main concerns were agronomy and horticulture, and their measurement of outflows were primarily for the calculation of fertiliser and nutrient losses. The three sites operated by the Institute of Hydrology were initiated to provide information for the development and testing of hydrological models of catchment runoff. Only the experiment at Withernwick was designed solely to study the effect of drainage on streamflow. At the majority of the sites the storm period response had not been analysed in detail. Such analyses as had been made were confined to a few storm events on the experimental sites at Ballinamore and Grendon where adjacent 'paired' drained and undrained plots enabled easy direct comparison of outflows. At both sites no consistent pattern had been found; for the Grendon site, Beven (1980) concluded that drainage 'can both increase and decrease peak discharge', whilst


*Figure 3.1* ***Location of the field drainage experiments. The sites are discussed in the text.***

for the Ballinamore site Burke *et al.* (1974) suggested that moling increased peak flows, although when their data were subsequently supplied to the MAFF as part of its review of drainage effects (Rycroft and Massey, 1975) the site was used (without comment) as showing that drainage reduced peak flows. This contradiction in the reported results from Ballinamore was referred to by Bailey and Bree (1981), although they could offer no explanation.

Thus, although most of these studies had been conducted some years ago, for a number of reasons the storm data from none of them had been fully analysed before this investigation. It was felt that all six sites were worth further analysis and, in the case of Grendon, the paired experimental plots were reinstrumented and run for a further two years, more than doubling the number of suitable storm events for analysis. At the six sites used in this study the average length of record was 31.8 months (range 9-68) for the undrained plots and 31.5 months (range 11-68) for the drained plots. General information about the sites is given in Table 3.2.

***Table 3.2 Summary of drainage experimental sites used in the study***

| Site | Grid Reference | | Area (ha) | Slope (%) | Long term annual Rain | Pot/Evap | Period of Study |
|---|---|---|---|---|---|---|---|
| Ballinamore | 7°46'W | 54°04'N | 0.005 | 17.6 | 1100 | 450 | Jun 65 - Nov 71 |
| Grendon | 0°59'W | 51°52'N | 0.25 | 0.5 | 650 | 500 | Apr 77 - Mar 82 |
| Blacklaw | 3°42'W | 55°43'N | 6.9 | 0.25 | 850 | 410 | Jan 59 - Dec 64 |
| Staylittle | 3°31'W | 52°26'N | 1.5 | 3.5 | 1800 | 470 | Nov 75 - Mar 78 |
| Tylwch | 3°39'W | 52°31'N | 1.7 | 2.6 | 1300 | 470 | Oct 75 - Jul 77 |
| Withernwick | 0°10'W | 53°48'N | 13.5 | 0.3 | 650 | 470 | Jan 74 - Mar 76 |

The six sites were all visited for this study with scientists closely responsible for their establishment and operation. This provided information on site characteristics, the definition of the plot boundaries, the drainage systems installed and the location of field instrumentation. In addition, where possible, copies were obtained of unpublished maps, diagrams, old correspondence and notebooks which had been kept at the time that the plots had been in operation. The available hydrometric data are summarised in Table 3.3. Due to the cost involved, none of the sites had replicated treatments. Site details such as groundslope and plot areas were obtained from large scale maps (at least 1:10,000 scale) and by field surveying. Another useful source of background information for the sites in England and Wales, was the staff in the local offices of MAFF. They were very helpful in providing both technical details of the drainage schemes at the study sites, as well as more general information regarding typical drainage schemes in their area. Data on the long-term climate at the sites were obtained from publications of the UK Meteorological Office and the Irish Meteorological Service, in addition to the rainfall depth-duration-frequency statistics given in Vol II of NERC (1975).

All the sites had soils with a low hydraulic conductivity resulting in a surface water drainage problem. This is the main reason for artificial drainage in Britain (Chapter 2). Apart from the peat soils at Staylittle and Blacklaw the drainage systems were fairly similar, with pipes at about 75 cm depth and secondary treatment to improve soil permeability above. This comprised mole drainage or subsoiling, typically at about 50 cm depth and 1.5-2 m spacing. In contrast the peat soil at Staylittle had pipe drains 9 m apart, with no secondary treatment and that at Blacklaw Moss was drained by open ditches 36 cm deep and 9 m apart.

***Table 3.3 Summary of data already available or collected during this study.***

| | Ballinamore | Grendon | Tylwch | Withernwick | Staylittle | Blacklaw |
|---|---|---|---|---|---|---|
| Type of study | Paired | Paired | Before/ After | Before/After | Before/ After | Before/ After |
| Flows | Volumetric | ¼90°v notch | 90°v notch | ½90°v notch | 90°v notch | ½90°v notch |
| Rainfall | Onsite | Onsite | Offsite | Nearby | Nearby | Onsite |
| Water table | Tensiometers | Tensio-meters | Dip wells | Dip wells | Dip wells | Dip wells |
| Water content | Gravimetric | Neutron probe | - | - | - | - |
| Soil water characteristic | √ | √ | - | √ | - | √ |
| Soil texture | √ | √ | √ | √ | √ | - |

At each of the sites a soil pit was dug and the profile was examined; some of the properties were recorded and the soil series identified. This work had already been done for all sites except Staylittle and Tylwch. For these two sites the soils were examined in the field for this study by a SSLRC soil surveyor, and soil samples were taken for subsequent particle size analysis in the laboratory at Wallingford. The land use, soils and type of drainage installed at the sites are summarised in Table 3.4. The identification of the soil series was important for several reasons. At sites where detailed soil properties had not been directly measured representative values were obtained from the national soil physical databank held by the Soil Survey and Land Use Research Centre (SSEW, 1984). Furthermore, in any future application of the results of this study to cases where the likely impact of a future drainage was of concern, the soil series (identified from soil maps or a limited site survey) would probably be the only soils information available. A description and explanation of the SSLRC soil series classification is given by Clayden and Hollis (1984).

There are many soil properties of hydrological relevance which can be either assessed for a profile in the field, or measured from samples in the laboratory. These range from broad descriptions of texture and structure to measurements of hydraulic conductivity and analyses of mineralogy and micromorphology. It was desirable for this study that the properties used were commonly measured or could be estimated from data that are generally readily available. Then the results from this study could be more easily transferred to other sites. A number of properties have been related to the soil series classification (SSEW, 1984) enabling their estimation from knowledge of the soil series at a site. This is important, since it would mean that, in principle, they can be estimated from soil maps. Where onsite measurements were available for the field site a check was made of how typical the soil was of its soil series.

***Table 3.4 Soils, land use and drainage***

| Site | Land use | Soil series | Soil type | Primary drainage | | Secondary drainage | |
|---|---|---|---|---|---|---|---|
| | | | | Depth & Spacing | | Depth & Spacing | |
| Ballinamore | Permanent grass | Hallsworth* | Clay | - | - | Mole drains<br>45 cm @ 1.1 m | |
| Grendon | Permanent grass | Evesham | Clay | - | - | Mole drains<br>45 cm @ 1.2 m | |
| Tylwch | Permanent grass | Cegin | Silty clay loam | 75 cm @ 13 m | | Subsoil/moles<br>45 cm @ 1.3 m | |
| Withernwick | Arable rotation | Burlington | Clay loam | 80 cm @ 10 m | | Subsoil/moles<br>50 cm @ 1.5 m | |
| Staylittle | Permanent grass | Crowdy | Peat | 75 cm @ 9 m | | - | - |
| | | Manod | Brown podzol | | | | |
| Blacklaw Moss | Rough grazing | Winter Hill* | Peat | Open drains<br>36 cm @ 9 m | | - | - |

* SSLRC equivalent to Irish or Scottish classification

Five soil parameters used by the SSLRC appeared to be of most hydrological relevance, and are described below. The first four are derived directly from examining the soil, either in the field or by analysis of samples taken back to the laboratory. The fifth is obtained by regular observations of water levels in dip wells over a number of years :

a) Texture

The texture refers to the size distribution of the mineral particles smaller than 2 mm (2000 μm). These are usually divided by size into :

Sand (60 - 2000 μm)
Silt ( 2 - 60 μm)
Clay ( < 2 μm)

NB Different countries and organisations use different definitions of size classes. This principally affects the division between clay and silt particles, for which the following values are in current use (Marshall and Holmes, 1988): 60 μm (SSLRC and BSI), 50 μm (USDA) and 20 μm (ISSS). Unless otherwise stated, the SSLRC classification is used in this report. The texture of a soil is described by the relative percentages of these three components, and may be plotted on a 'trilinear' diagram (Fig 3.2).

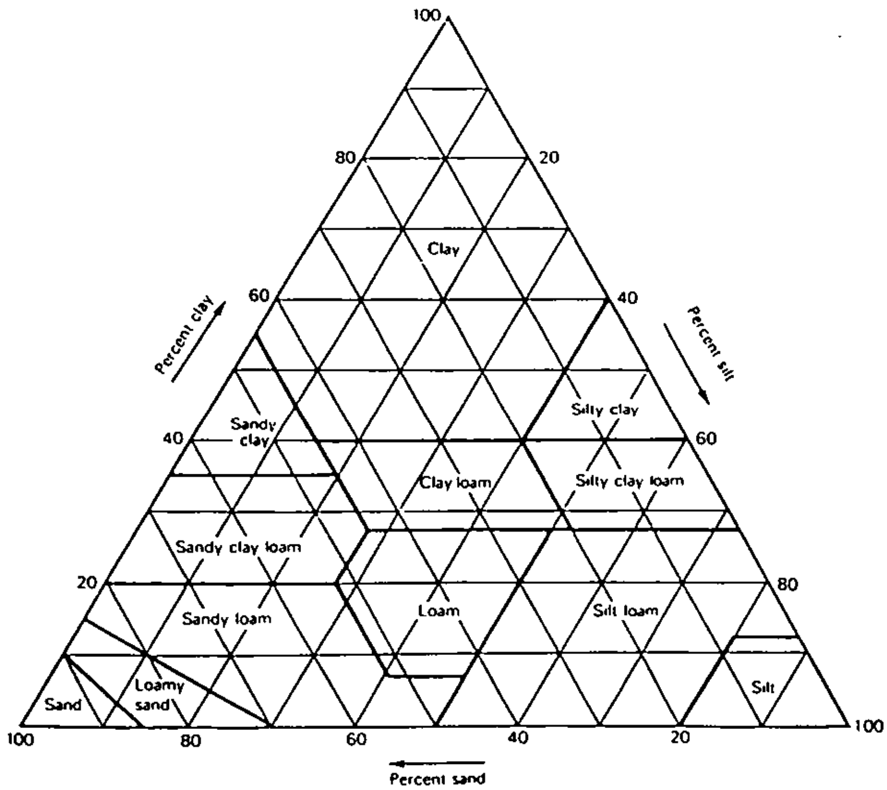



*Figure 3.2 Trilinear plot of mineral soil texture, showing the clay, silt and sand percentages by weight*

Again, different organisations and countries vary in their nomenclature of the different textural classes, and the SSLRC system is used in this report. In broad terms, a 'clayey' soil has > 35% clay, whilst soils with < 35% clay are called 'loamy'. The loamy soils can be subdivided into 'clay loams' (18-35% clay) and 'sand or silt loams' ( < 18% clay). These terms may be used for one layer or 'horizon' in a soil, or for the whole profile. In the latter case this is applied to the main texture overall in the top 80 cm. In soil profiles with two (or more) very different layers, the description would be given as 'texture of upper layer' over 'texture of lower layer'. Methods of particle size analyses in the laboratory are described in the literature (e.g. Avery and Bascomb, 1974; Klute, 1986a), and soils can be assigned to a broad textural class in the field by an experienced soil surveyor.

b) Depth of gleying

Gleying is an important indicator of seasonal waterlogging. The reduction, mobilisation and removal or redeposition of iron compounds by micro-organisms or the by-products of decaying organic matter produces distinctively coloured soil horizons. Periodic waterlogging allows intermittent aeration and re-oxidation, leading to the formation of grey, yellowish and ochreous mottles due to oxidized ferric iron compounds. Persistently waterlogged soils are usually wholly grey or bluish grey. A soil which is waterlogged due to impeded surface water drainage caused by an impermeable subsoil is called a 'stagnogley', or 'stagnohumic gley' if organic matter is accumulating on the surface. If the soil is permeable, but waterlogged due to high groundwater, it is known as a 'groundwater gley'. Climate may also exert a strong influence on the incidence of waterlogging.

A gleyed horizon can be identified in the field from a freshly exposed soil profile, or by using a hand auger. Gleyed horizons are identified in soil profile descriptions by the subscript 'g'. It takes about a century for waterlogging symptoms to develop, but once formed they are relatively permanent. Thus, gleying will still be evident in artificially drained soils, representing their pre-drained soil water regime, rather than current conditions. The depth to gleying can also be estimated for a given soil series.

c) Depth to a limiting slowly permeable horizon

This can be estimated in the field from the soil structure and texture, or from soil physical properties measured in the laboratory. It is not easy to provide an exact physical definition of an impeding or 'impermeable' horizon, although a number of criteria have been proposed. Luthin (1957) suggested that horizons with a saturated hydraulic conductivity of less than 0.1 m per day (0.4 cm/hr) are effectively impermeable, in terms of their contribution of water to field drains. Alternatively, it may be argued that it is the relative conductivities of the different horizons that is important in controlling water movement and some authors have used a decline in conductivity of one order of magnitude, to indicate the presence of an impeding layer. In practice, even these somewhat arbitrary values are of restricted utility, due to the very limited number of reliable measurements of soil hydraulic conductivities. Nevertheless, despite the problems encountered in obtaining values of hydraulic conductivity, it is generally accepted that there is a broad relation with other, more easily measurable, soil properties including texture, structure and pore size distribution. The SSLRC have developed a general relation between the saturated hydraulic conductivity of a soil and its air capacity and packing density. The air capacity is defined as the percentage by volume of air filled pores at 0.05 bar (5 kPa) suction (equivalent to pores > 60 $\mu$m), and indicates the volume of easily drained interconnected pores. This is important both for short-term soil water storage and for water movement through saturated soils. The packing density is calculated from the bulk density of the soil, modified to take account of the unavailable water held by the clay particles. It is defined as:

Packing density = Bulk density + 0.009 x (%Clay)

The air capacity of a horizon is usually in the range 5-15%, and the packing density is usually 1-2 g/cm$^3$. The definition of the slowly impermeable horizons from these two parameters, used by the SSLRC for mineral soils, is shown in Figure 3.3.

The air capacity is clearly more important than the packing density. The SSLRC have detailed laboratory analyses, including soil water retention data, for about 1,500 soil profiles (about 3,500 individual soil horizons). This enables the calculation of air-water relations for all the main soil series (Hall *et al.*, 1977). It is recognised there will be cases where this definition of an impeding horizon is difficult to apply, for example with profiles in which these properties change gradually with depth, or for horizons with 'borderline' values. The boundary between two horizons may be very abrupt, or if very 'wavy' it could vary vertically by up to 30 cm. The topsoil layers may have a large variation in soil physical properties due to land use.

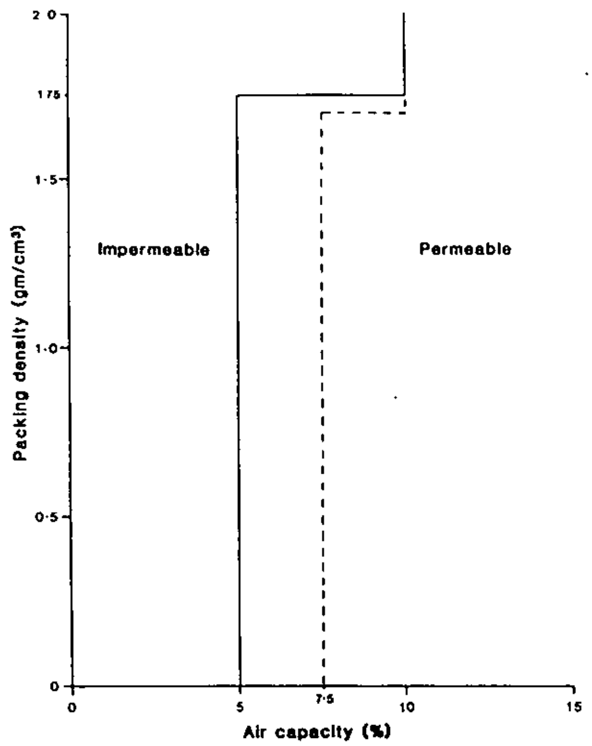



***Figure 3.3 Definition of impeding slowly permeable horizon in terms of its air capacity and packing density***

In practice the depth to slowly permeable horizon often corresponds to the topsoil layer. For arable land this will be the plough layer; as a broad guide the depth of ploughing depends on soil type, increasing from about 25 cm on clay soils to about 40 cm for sandy soils. In soils with a high clay content, arable cultivation could result in the slowly permeable layer being at the surface, due to compaction of the soil by heavy machinery. Soil surveyors can distinguish between permanent grass (pasture or meadow) and temporary grass (part of an arable rotation) by the species present.

The depth to an impermeable layer in a soil can be determined in a number of ways, with differing degrees of accuracy. If laboratory measurements of air capacity and packing density are not available, the impeding layer may be estimated in the field from a profile pit based on assessments of the texture, density and structure of the component horizons. Alternatively a simpler, but less accurate estimate, can be made from auger samples, based on texture alone.

d) Integrated air capacity

This is a measure of the potential short-term water storage capacity of a soil profile, and is calculated as the product of the air capacity of each horizon and the depth of the horizon. This gives an equivalent depth of water (expressed in mm) that the soil can readily absorb or drain. There are differences in the calculation of this measure, depending upon the depth of the soil profile that is considered. Some soil surveyors use a standard depth such as 1.0 or 1.2 m for this integration regardless of the component horizons. In this study, the integrated air capacity was computed only for those horizons above the slowly permeable horizon. In many profiles there will be little difference in the computed values to either this or a standard depth because of the small air capacity of the slowly permeable horizon. There are other profiles, however, in which very permeable layers, with a high air capacity lie underneath a slowly permeable horizon. An example of this is the Tedburn soil series in which a clay soil overlies a porous layer comprising fractured shaly material.

e) Wetness class

This is based on the frequency of the measured depth of the water table. A classification has been developed by the SSLRC using 900 site-years of data from dip wells or tensiometers, and uses the amount of time that the water table is above 40 cm and 70 cm depths (Robson and Thomasson, 1977). The classes are as summarised in Table 3.5.

*Table 3.5 Definition of soil water regime classes*

| WETNESS CLASS | No of days in year nearer surface 40 cm | 70 cm |
|---|---|---|
| I | | < 30 days |
| II | | 30 - 90 |
| III | | 90 - 180 |
| IV | < 180 | > 180 |
| V | 180 - 335 | > 335 |
| VI | > 335 | |

Although the frequency of the water table at a shallower depth (e.g. 20 cm) would be more relevant to storm runoff generation, it was not calculated by the SSLRC because it cannot be adequately described by weekly readings, and would require many more years of data than are currently available to get a sufficiently large sample for accurate determination.

Soil properties for all the study sites were discussed with personnel at the SSLRC, and in the case of the Irish site at Ballinamore and the Scottish site at Blacklaw Moss the soil descriptions from the respective national soil survey organisations were assigned to the corresponding SSLRC soil series classification. The soils at the study sites represent a fairly narrow range of the possible soil types in Britain, in that they all have a surface water drainage problem. These are however, the main type of soils that are drained in Britain (Chapter 2). They can be divided according to the SSLRC classification into two main groups of soils. Pelosols are clayey soils which swell on wetting up in winter to become impermeable and waterlogged, leading to some mottling. They become porous on cracking in summer. There is no strong mottling above 40 cm depth, which may be taken to indicate that they are not waterlogged above this depth for more than about 90 days per year. In contrast, surface water gleys are mottled above 40 cm, indicating they are waterlogged for prolonged periods. There is no textural definition for this class of soils (cf pelosols), but in addition to the surface waterlogging they have an impermeable layer within 80 cm of the surface. Two subgroups of surface water gleys are of interest to this study, and are distinguished by their clay content. The pelo subgroup are clayey to the surface. They are waterlogged near the surface for much of the year and do not dry out sufficiently to develop significant cracking. The impeding layer in these soils is usually within 40 cm of the ground surface. The non-pelo subgroup are loamy, silty or sandy soils and the impeding layer causing waterlogging is usually deeper than 40 cm below the surface.

The values of these soil parameters measured at the sites are summarised in Table 3.6, together with average values for those soil series from the SSLRC database, and the sites themselves are discussed in detail in the following sections. The field description and assessment of soil profile properties is described in Hodgson (1974), and the SSLRC soil series classification is outlined in Clayden and Hollis (1984). It may be possible to use the shallower of either the depth to gleying or the depth to an impeding layer as a measure of the likely available winter water storage capacity of the soil.

*Table 3.6 Mineral soil properties at the study sites*

| Site | SSLRC Soil series | SSLRC sample size | Depth to impermeable (cm) | | Depth to gleying (cm) | | Topsoil clay (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | Onsite | SSLRC | Onsite | SSLRC | Onsite | SSLRC |
| Ballinamore | Hallsworth | (7) | 25 | 24 ± 5 | 5 | 20 | 34 | 38 |
| Grendon | Evesham | (8) | 20 | 24 ± 6 | 20 | 60 | 55 | 52 |
| Tylwch | Cegin | (4) | 36 | 37 ± 10 | 0 | 25 | 23 | 31 |
| Withernwick | Burlingham | (4) | 45 | 46 ± 7 | 45 | 50 | 20 | 22 |

### 3.2.2 Ballinamore

The study site near Ballinamore in Ireland was operated by An Foras Taluntais (The Agricultural Institute) for approximately six and a half years, from June 1965 to November 1971 (Burke *et al.*, 1974). Two small plots each 22 m by 2.4 m, were instrumented on a $10^{o}$ hillslope (Fig 3.4).

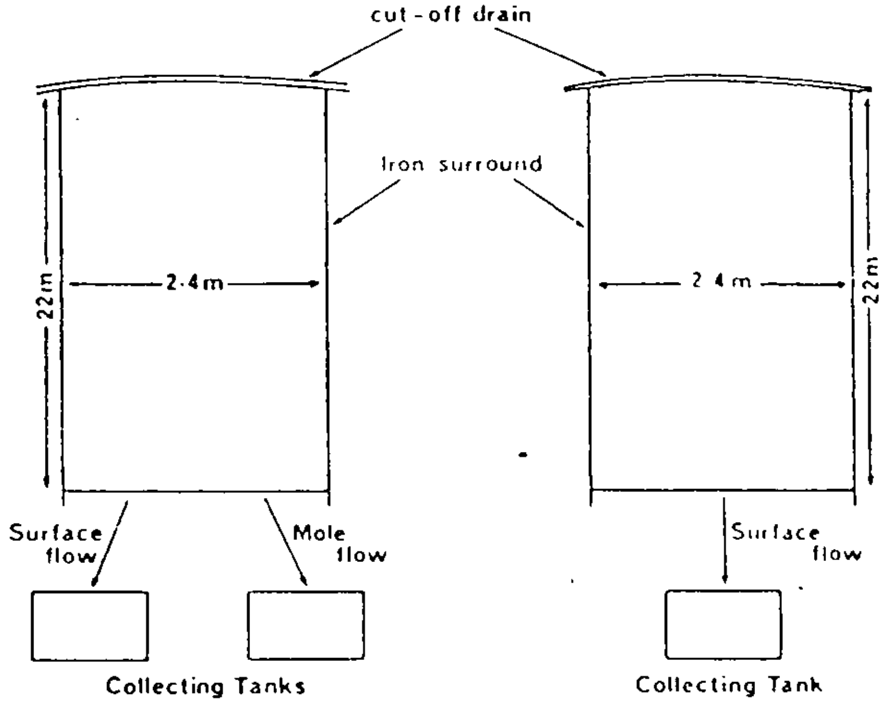



*Figure 3.4 Ballinamore field drainage experiment showing the study site and instrumentation*

Each plot was isolated from outside surface layer flows by a 30 cm deep ditch at the upslope boundary, to act as a cutoff drain, and had a 15 cm deep impermeable boundary around the remaining three sides. At the downslope end of each plot an eave and gutter at about 8 cm depth collected overland flow and subsurface flow through the grass root layer zone and led them to flow recorders. Flows were measured as cumulative volumes in large collecting tanks. Each tank was one cubic metre in capacity and equipped with a water level recorder. Water levels were continuously recorded on weekly charts giving a time scale of 2.5 mm/hour and a vertical scale representing a 16 mm rise for every 1 mm outflow from the plots. The tanks were emptied by manually opening a valve when the charts were changed and additionally, as necessary, during the week. As the plots were situated at an AFT research station and visited at least daily, there were only a few rare times, during large night-time storms that the tanks overflowed and flows were unrecorded. After a 10 month 'control' period to verify that the outflows from the two plots did not differ, one of the plots was drained in April 1966, by two mole drains at 45 cm depth and 1.1 m spacing. Flows from these drains were led to a third flow recorder.

The whole area was under permanent pasture and to prevent structural damage due to poaching of the soil under animal hooves neither plot was grazed during the study, the grass being cut and removed by hand. The soil at the site is a surface water gley of the Ballinamore soil series (AFT, 1973) and is typical of many of the glacial mineral soils developed on carboniferous shales in Ireland. It comprises a topsoil layer 25-30 cm deep with a good structure, overlying a structureless clay subsoil. The soil profile at a nearby site on the field station, with a slightly thinner topsoil, is described in Table 3.7.

*Table 3.7 Soil profile description for Ballinamore*

| Horizon | |
|---|---|
| A1 (0-5 cm) | Clay (36% clay, 43% silt) Weak medium subangular blocky structure. Abundant fine root channels, with iron staining. |
| A2g (5-21 cm) | Clay loam (32% clay 45% silt) Very weak medium subangular blocky. Prominant yellowish-red mottling. |
| Btg (21-52 cm) | Clay (46% clay 38% silt) Massive to very weak coarse prismatic. Yellowish-brown mottling. |
| Cg (52-130 cm) | Clay (37% clay 44% silt) Massive to coarse prismatic. Olive brown mottles. |

NB The textural descriptions used above refer to those used by the SSLRC. The Irish soil survey classification uses a higher minimum clay content (> 40%) to define a clay horizon than the SSLRC (> 35% clay).

The soil corresponds to the Hallsworth soil series in the SSLRC classification (J. Hollis, pers. comm.). This is a surface water gley soil and due to its high clay content would be termed a pelo-stagnogley. The depth to an impermeable layer would usually correspond to the topsoil depth. Laboratory measurements made by the AFT on small soil cores indicated that whilst the topsoil below the root mat was fairly permeable (saturated hydraulic conductivity about 1.3 cm/hour), the subsoil was much less permeable (saturated hydraulic conductivity only about 0.00025 cm/hour). The shallow depth of the topsoil above this low permeability subsoil, together with the high rainfall (annual average 1100 mm) kept the undrained soil waterlogged for much of each winter.

Given this permeability contrast with depth of four orders of magnitude, and the fact that all flows from the upper much more permeable layer were measured, it was felt the experimental design could be reasonably expected to account for the vast majority of storm period flows; any unmeasured flows through the low permeability subsoil would occur as baseflow at this site, and so be of little relevance for studies of storm period flows to stream channels. Rainfall was recorded using a tilting siphon autographic raingauge, equipped with a daily chart and a daily read storage check gauge. Soil water potentials were measured in each plot by a set of tensiometers at depths of 7.5, 15, 30, 45, 60 and 90 cm.

### 3.2.3 Grendon Underwood

The study site at Grendon Underwood, Buckinghamshire, was instrumented by the Institute of Hydrology. It is situated within the larger (18.5 $km^2$) catchment of the river Ray, and studies of the main catchment runoff are described in Chapter 6. The field drainage study is on a permanent pasture site which according to the farmer had not been ploughed for at least the last 60 years. The normal farming use of growing hay and grazing by cattle were continued during the period of this investigation. The area has pronounced 'ridge and furrow' topography, which was a traditional land management practice common in many parts of Britain (Green, 1975; Raistrick, 1967; Muir, 1987), ploughing the soil to form longitudinal ridges to provide local areas of improved drainage. At the study site these ridges are 7-10 metres apart and are aligned directly downslope. The vertical range is approximately 30-40 cm. An earlier study found that such ridges controlled surface layer flow, with each ridge forming an effective barrier, and reducing any plot 'edge effects' (Childs, 1943).

Two plots, each about 0.25 ha, were instrumented in April 1977 and measurements were continued for 5 years until March 1982. One plot was mole drained whilst the other remained undrained (Fig 3.5). The mole drains were at 45 cm depth and at 2 m spacings. Total flows were collected at the downslope end of each plot by a tile drain backfilled with gravel (30 cm deep drain for the undrained plot and 90 cm deep for the drained plot). Each drain led to a v notch weir with a water level recorder. In the first year chart recorders were used. These had a vertical gearing of 1:1 and a horizontal time scale of 2.5 mm/hr (Truesdale and Howe, 1977). In the following years these were supplemented by water level sensors (Strangeways and Templeman, 1974) linked to a data logger, giving synchronised water levels and rainfall at 5 minute time intervals. Soil water conditions in the two plots were monitored using tensiometers to measure soil water potential (and hence the position of the water table and the direction of water movement) and neutron probe measurements of soil water content.

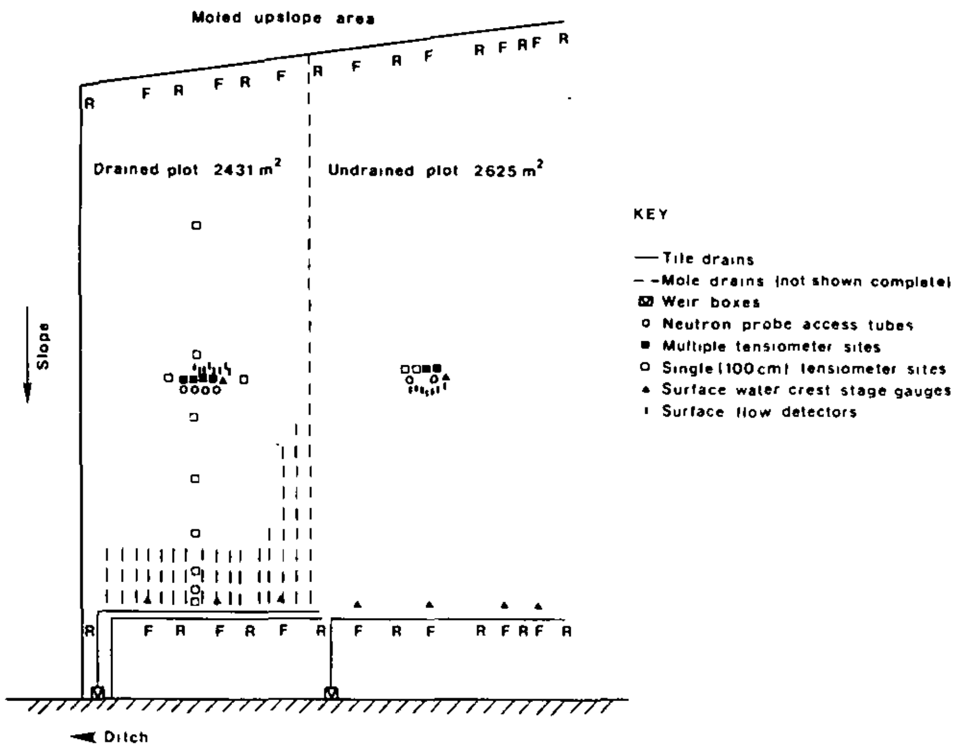



*Figure 3.5 Grendon field drainage experiment showing the study site and instrumentation*

The soil at the site belongs to the Evesham soil series (Avery, 1959). This is a gleyed calcareous clay soil and is termed a calcareous pelosol in the SSLRC classification. Its depth to an impeding layer is usually equivalent to the topsoil depth. This soil has poor natural drainage resulting in surface ponding and waterlogging due to its low hydraulic conductivity (e.g. Jarvis, 1973). The clay soil shrinks and cracks in summer, making it more permeable, but in winter the cracks close up as the soil is wetted. A profile description is given in Table 3.8. Germann and Beven (1981) measured the hydraulic characteristics of the soil at the study site using a large (25 cm diameter) core taken from the soil profile at 20-35 cm depth, and including the topsoil - subsoil interface. Their findings are summarised in Table 3.9, and indicate that macroporosity (small fissures and earthworm channels) although comprising only a small part of the total volume may have a very important effect on flow rate, even in a wetted sample.

*Table 3.8 Soil profile description for Grendon*

| Horizon | |
|---|---|
| AH | Clay with abundant grass roots |
| (0-4 cm) | Very permeable. |
| Ah | Clay (55% clay 35% silt) well structured |
| (5-20 cm) | with many grass roots. Some |
| | yellowish-red mottling. |
| Bg | Clay (51% clay 34% silt) weak |
| (20+ cm) | coarse prismatic. Olive brown mottling. |

The depth to an impermeable layer and the depth to gleying are both 20 cm.

*Table 3.9 Hydraulic properties of the Grendon site soil*

| Pressure potential (kPa) | Hydraulic conductivity (cm/hr) | Drained porosity (%) |
|---|---|---|
| 0 | 0.47 | 0 |
| 0.5 | 0.11 | 4.5 |
| 5.0 | 0.001 | 6.0 |

Many of the storm hydrographs recorded in the first winter (1977/78) were found to have been affected by backing up of water from the outfall ditch. This problem was eliminated when the ditch was cleaned and regraded in summer 1978 (Beven, 1980). Measurements were continued for a second winter (1978/79) and the site was closed in April 1979. In view of the proximity of the site to Wallingford, the recent nature of the drainage work and the initial problems which had resulted in the loss of much of the early flow data, it was decided for this study to reopen the site. Accordingly, it was instrumented again in autumn 1980 and run for two winters (1980/81 and 1981/82). This extension to the site record increased the number of suitable storms for analysis from 11 to 39.

### 3.2.4 Tylwch

The study site near Llanidloes in Powys, mid-Wales, was operated by the Institute of Hydrology for nearly two years from October 1975 - July 1977. Contacts with the local MAFF office at Llandrindod Wells had identified a field of approximately 1.7 ha as being due to shortly have field drainage installed. The site is used for pasture, and before drainage had a heavy growth of *Juncus* rushes; standing water was observed on the lower part of the field for long periods in the winter. With agreement from the farmer a weir, recording raingauge and weekly-read storage gauge were installed, together with a transect of boreholes across the field to give an indication of soil water conditions (Fig 3.6).

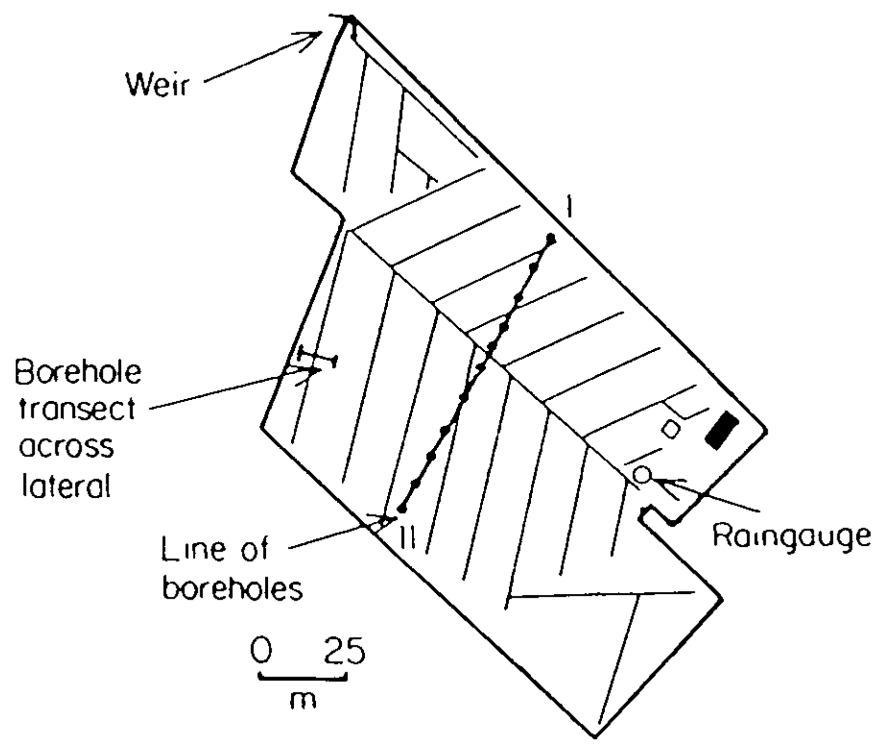



*Figure 3.6 Tylwch field drainage experiment showing the study site and instrumentation*

The lower end of the field had a ditch, which enabled the total storm outflow (overland flow, drain flow and interflow) to be measured using a v notch weir and water level recorder (Truesdale and Howe, 1977). This had a 1:1 gearing and a weekly chart, providing a time scale of 2.5 mm/hr. Soil water conditions were monitored in 11 dip wells. These were augered by hand to about 80 cm depth, being limited by a rocky horizon at 70-90 cm. The wells were lined with drainage tiles to ensure stability and to provide a fixed datum level for the water depth measurements. The tops were covered to prevent the direct entry of precipitation, and the water levels were measured at weekly intervals with an acoustic sensor.

The soil at the site had been identified by the MAFF drainage advisor as belonging to the Cegin series. To obtain further information the site was visited by a SSLRC soil surveyor and two pits were dug and profile properties examined in the field. The soil was confirmed as belonging to the Cegin soil series (R. Hartnup, pers. comm.). This is a surface water gley soil with a silty clay loam texture, and is classified as a cambic stagnogley. It has a lower clay content than, say, Evesham or Hallsworth soils and the waterlogging is due to its occurrence in areas with a higher net rainfall. The depth to impermeable layer is generally the same as the topsoil depth (usually > 40 cm) but this can be very variable, being shallower on sloping land and deeper on level ground. These soils are seasonally waterlogged and strongly gleyed within 35 cm of the ground surface, and have a relatively impermeable B horizon (Lea, 1975: Rudeforth *et al.*, 1984). A description of the soil profile at the site is given in Table 3.10. There was evidence of gleying up to the surface, and a limiting slowly permeable horizon at 36 cm depth. Particle size analyses were carried out at the Institute of Hydrology (BSI, 1967).

*Table 3.10 Soil profile description for Tylwch*

| Horizon | |
|---|---|
| Apg (0-25 cm) | Silty clay loam (19% clay, 70% silt) Moderate medium angular blocky structure. Strong brown mottling common. Plough layer. |
| ABg (25-36 cm) | Clay loam (32% clay 45% silt) Moderate medium angular blocky. |
| Bg (75+ cm) | Silty clay loam. Weak coarse angular blocky structure. Many reddish yellow mottles. |

The depth to an impermeable layer is 36 cm, and the profile is gleyed to the surface.

The artificial drainage comprised 75 mm diameter clay pipes laid at 12.8 m spacings at 75 cm depth. The trenches were backfilled with quarry gravel to act as a permeable fill, and the soil was then subsoiled at right angles to the pipes at 45 cm depth and 1.3 m spacings. Unfortunately the recording raingauge on the site was inoperative for much of the time, preventing its use in the analysis of storm rainfall-runoff relations. Whilst sufficient data were available for its use in the period prior to drainage, it was only operative for one large storm event after drainage. Consequently it was necessary to seek an alternative source of information on storm rainfall profiles, and comparisons were made between the available storm records at this gauge and at other recording gauges in the area, the existence of which were found by using the nationwide register of recording raingauges (Farquharson, 1976). The gauge recording the most similar storm profiles to those at the drainage site was one operated by the Severn-Trent Water Authority at Caersws (Fig 3.7). This is situated about 14 km to the east of Tylwch, and has a somewhat lower average annual precipitation (1941-70 average was 910 mm/yr).

Since the object of study was to identify any difference in the response between the two time periods, before and after drainage, consistency of analysis was of paramount importance. Whilst it could be argued that the onsite record should be used whenever it was available, this would have resulted in an effective change of gauges from onsite before drainage to Caersws after drainage. It would clearly be undesirable to change gauges at

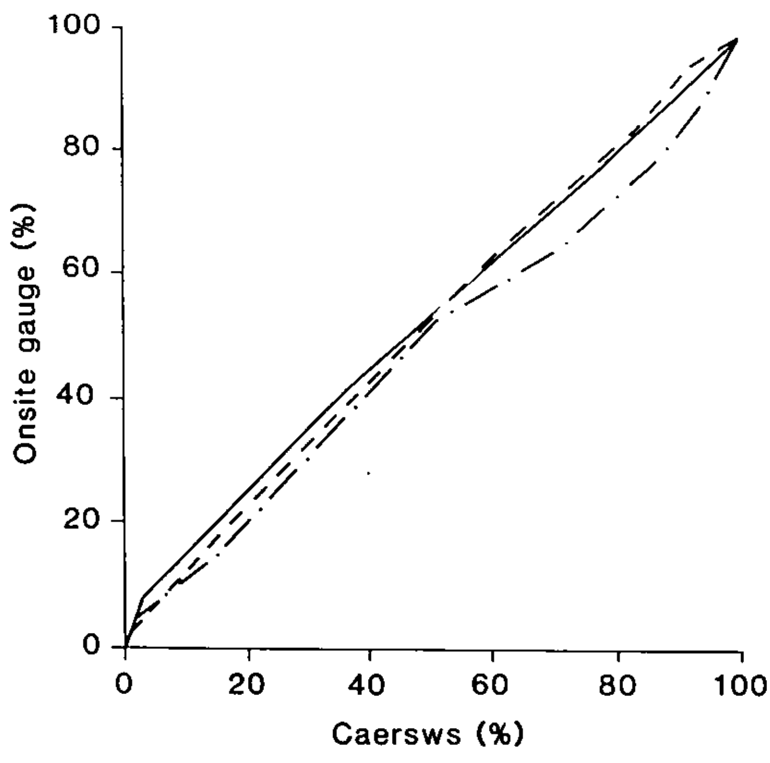



*Figure 3.7 Comparison of recorded storm profiles at the onsite gauge at Tylwch and at Caersws*

about the same time as the drainage, since there would inevitably be some uncertainty regarding the cause of any observed change in the rainfall-runoff relation between these periods. Therefore, for each storm the rainfall profile at Caersws was scaled by the measured depth at the daily gauge at Garth Fawr (annual 1941-70 precipitation 1110 mm), situated 5 km to the south east of Tylwch (Table 3.11).

*Table 3.11 Comparison of daily rainfall (mm) at Tylwch and at the nearest daily read storage gauge at Garth Fawr*

| Storm period | Onsite gauge | Garth Fawr |
|---|---|---|
| 15/11/75 | 14.7 | 12.5 |
| 1/01/76 | 18.7 | 19.5 |
| 9/01/76 | 18.0 | 15.3 |
| 10/01/76 | 2.6 | 2.4 |
| 25/03/76 | 4.8 | 4.6 |
| Total | 58.8 | 54.3 |

Mean absolute difference 1.2

## 3.2.5 Withernwick

The site at Withernwick, in Holderness, was operated by the University of Hull as a postgraduate research project (Ryder, 1979). It lies within the 16.5 $km^2$ Catchwater Drain research catchment (Ward, 1982), and studies of the main catchment runoff response are described in Chapter 6. The drainage study area comprised four fields totalling 18.3 ha which were instrumented in January 1974 and detailed measurements continued for nearly 3 years (Fig 3.8). The land had been used since the 1960s for arable rotation of cereals and grass.

Field 1 was used for grass, and field 4 for cereals throughout the study. Field 2/3 was used for grass before drainage and for cereals in the period afterwards. Approximately 25% of the area had been recently drained (in 1972), and the remainder was drained in the summers of 1974 (56%) and 1975 (19%). The southern boundary of the study area was formed by the topographic watershed, and the eastern and northern boundaries by existing ditches. Little water would have entered the study area from the west since the fields there already had an efficient field drainage network. Flows from an area of 9 ha entered the study area via a channel which formed the main watercourse through the experimental area. Inflows and outflows from the study area were measured in this ditch by v notch wiers at sites 'A' and 'B'. The inflows to the upstream weir at A also provided a 'control' catchment against which any changes in the hydrological response of the study area could be measured.

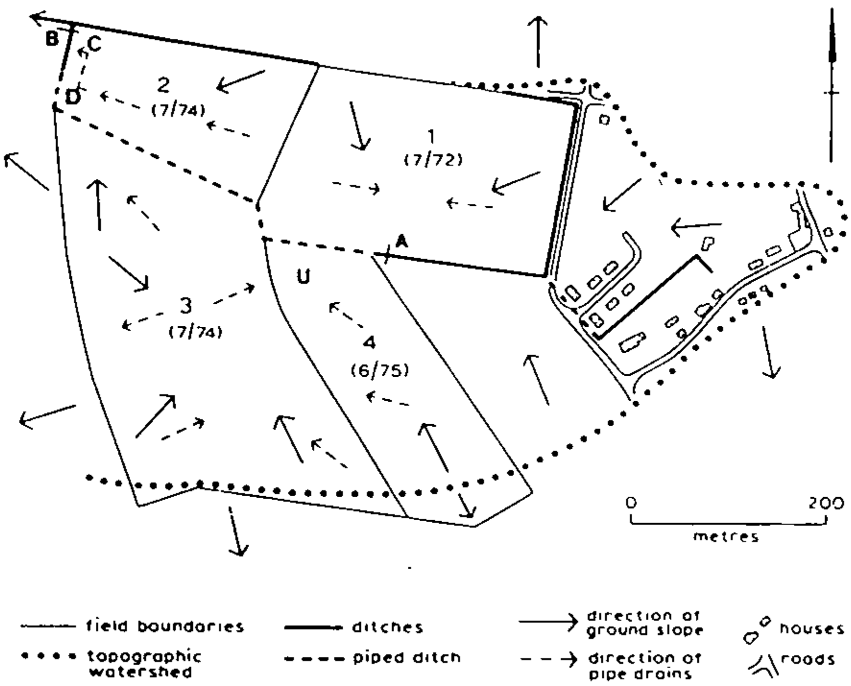



***Figure 3.8 Withernwick field drainage experiment showing the study site and instrumentation***

Water levels were recorded on weekly charts with gearings of 1:1.33 (weir A) and 1:2.66 (B) at a time scale of 2.5 mm/hr. Rainfall was measured at Westlands Farm weather station less than 1 km from the site (Ward, 1982). From December 1974 water table depths on drained and undrained land were measured in narrow bore (10 mm) dip wells equipped with weekly chart recorders (Harris, 1977). The drainflow from field 2 was measured for 18 months (October 1974 - March 1976) by a weir on the single outfall, and flows in a 75 mm diameter lateral drain in the field were measured using a vane-in-orifice meter (Rands, 1973).

The soil at the site is predominantly Holderness series (Furness, 1985), but following a redefinition of the soil classes, would now be classified as Burlingham series (J. Hollis, pers. comm.). This is a loamy soil belonging to the Brown Soil group of the SSLRC classification. The Burlingham series has a slowly permeable clayey subsoil (usually below 40 cm), and only slight mottling above 40 cm (Jarvis *et al.*, 1984). It is rarely strongly gleyed, probably due to the low rainfall, and is classified as a stagnogleyic argillic brown earth. A soil profile description is given in Table 3.12, based on a soil pit dug by the SSLRC 400 m from the study site. In addition, soil cores, 10 cm in diameter, were taken from the fields at the time of their drainage,and the vertical saturated hydraulic conductivity was measured in the laboratory using a falling head apparatus. They comprised samples from the topsoil and from the drain trenches (50-110 cm depth). Values for the bottom of the drain trenches averaged 0.08 cm/hr which is similar to in-situ measurements of subsoil conductivity, by the MAFF, using the auger hole method on similar soils elsewhere in Holderness. Topsoil values for the cores at Withernwick were only about double this value, and this may be the consequence of compaction by farm machinery (or indeed by the drainage machinery).

*Table 3.12 Soil profile description for Withernwick*

| Horizon | |
|---|---|
| Ap (0-30 cm) | Clay loam (20% clay, 32% silt). Weak, coarse blocky structure. |
| Bw (30-45 cm) | Clay loam (21% 33% silt) Moderate coarse blocky structure. |
| BG(g) (45-93 cm) | Clay loam (20% clay 42% silt) Massive structure, Dark brown mottles common. |

NB Due to their glacial parent material soils of the Burlingham series may have very variable depths to a slowly permeable horizon. It is, however, usually deeper than 40 cm with 45 cm as a typical value. This profile was selected from a number of SSLRC profile descriptions in the vicinity as being reasonably representative.

Drainage at the site comprised 75 mm clay pipes, generally laid at 10.3 m spacings and at 80 cm depth. The drain trenches were backfilled with excavated soil, since in common with other drainage schemes in this area, the cost of transporting stone for permeable fill is too high. The land was then subsoiled at right angles to the drains at approximately 1.5 m spacings and 50 cm depth. This was deeper than the 'critical depth' (e.g. Spoor and Godwin, 1983) and produced a compacted channel 7 by 10 cm in cross-section. Such a hybrid secondary treatment, intermediate between true moling and subsoiling, is in fact very common in practice in Britain (Trafford, 1975). The benefit of drainage at this site was evident in the 1976 drought when the drained land gave noticeably higher crop yields (R. Furness, pers. comm.). This was the result of the better root development on the drained land enabling the plants to reach water deeper in the soil profile.

### 3.2.6 Staylittle

The site in Powys, mid-Wales, was instrumented by the Institute of Hydrology for nearly two and a half years, from November 1975 to March 1978. It comprised one field 1.5 ha in area which was instrumented about 14 months prior to its drainage in March 1977. The land was used for pasture (Fig 3.9). Flows were recorded using a v notch weir and water level recorder with a 1:1 gearing and a weekly chart giving a time scale of 2.5 mm/hr (Truesdale and Howe, 1977).

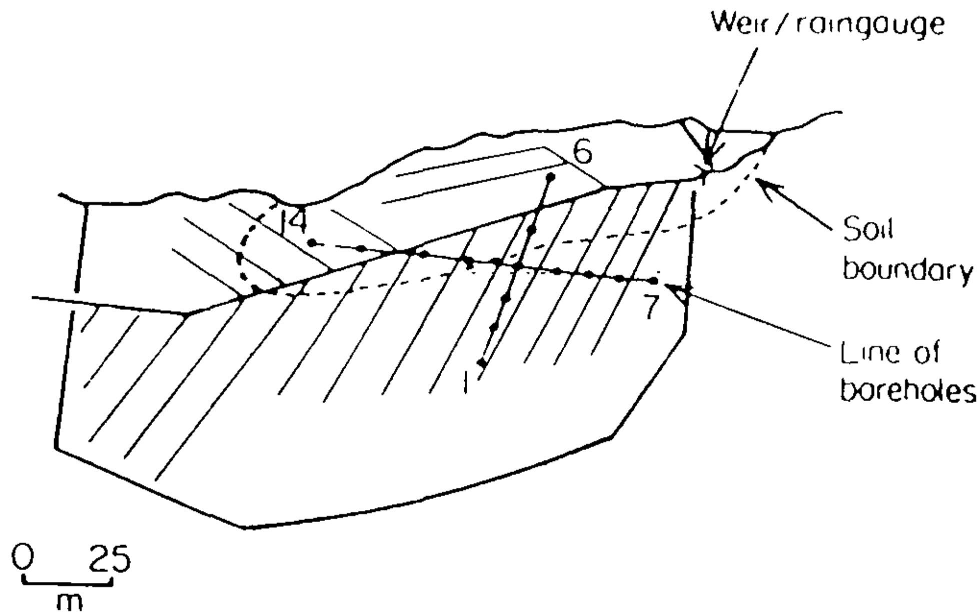



*Figure 3.9 Staylittle field drainage experiment showing the study site and instrumentation*

A recording raingauge was operated on the site, together with a weekly read standard storage gauge. Due to gaps in the record of the onsite recording raingauge, particularly prior to the drainage, it was decided for consistency over the whole study period to use the records from a nearby raingauge at Tanllwyth. This gauge 6 km to the west, is operated by the Institute of Hydrology. Comparison of storm rainfall profiles at Tanllwyth with the available record at the onsite gauge indicated a close degree of similarity (Fig 3.10).

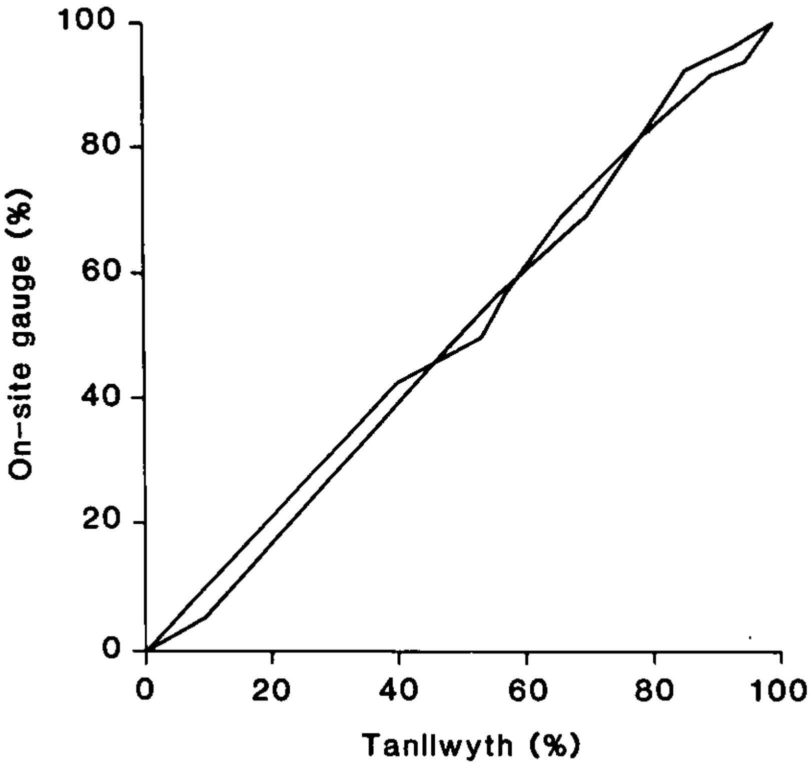



*Figure 3.10 Comparison of recorded storm profiles at the onsite gauge at Staylittle and at Tanllwyth*

For each storm the total rain depth at Tanllwyth (annual 1941-70 precipitation 2200 mm) was corrected to match that at Staylittle (annual precipitation about 1800 mm) by scaling it to equal the arithmetic mean of two daily gauges near Staylittle at Dolydd (1780 mm/yr) and Dol Bachog (1597 mm/yr). This was found to be the combination of nearby daily gauges which most closely matched the onsite measured falls (Table 3.13).

*Table 3.13 Comparison of daily falls for the largest storm events (mm)*

| Storm period | Onsite gauge | Dolydd | Dol Bachog | (mean) |
|---|---|---|---|---|
| 30/6-1/7/77 | 46.0 | 43.2 | 39.6 | 41.4 |
| 9-10/9/77 | 40.5 | 49.2 | 34.0 | 41.6 |
| 19-20/11/77 | 49.0 | 54.3 | 46.2 | 49.8 |
| 23/11/77 | 43.5 | 45.7 | 38.6 | 42.2 |
| 30-31/10/77 | 55.5 | 50.4 | 50.5 | 50.5 |
| Total | 234.5 | 242.8 | 208.9 | 225.9 |
| Mean absolute difference | | 4.8 | 5.1 | 2.5 |

The soil at the site had been classified by the MAFF drainage advisor as belonging to the Ynys soil series. This series was subsequently renamed

Wilcocks series by the SSLRC. To obtain further information on the soil properties, the site was visited by a SSLRC soil surveyor, who identified two soil series, Wilcocks and Crowdy (R. Hartnup, pers. comm.). The Crowdy series is defined as an oligo-amorphous raw peat soil at least 40 cm thick (Rudeforth *et al.,* 1984). These soil are more or less permanently wet. The Wilcocks soil is a stagno-humic surface water gley, comprising a peaty or humose topsoil less than 40 cm thick, overlying clay loam mineral horizons. The depth to a slowly permeable horizon is generally more than 40 cm, but due to its peaty topsoil the soil has a very limited rain water storage capacity. Particle size analyses were carried out at the Institute of Hydrology (BSI, 1967) and indicated that the underlying mineral horizons had a clay loam texture. A site profile description for the dominant soil type at the site, the Crowdy series, is given in Table 3.14.

***Table 3.14 Soil profile description for Staylittle***

| Horizon | |
|---|---|
| HLP (0-24 cm) | Very dark brown amorphous peat |
| HP (24-74 cm) | Black amorphous peat |
| Cg (74+cm) | Clay loam / silty clay loam (20% clay, 57% silt). Grey matrix, weakly developed structure. |

Soil water conditions were monitored in two transects of dip wells. The wells were generally less than 75 cm in depth, being limited by a rocky horizon at about 50 cm in the Wilcocks profiles and a semi-liquid peat/clay layer at about 80 cm in some of the Crowdy profiles. The wells were lined with drainage tiles to provide stability and a fixed datum reference level for the depth measurements. The tops were covered to prevent direct entry of precipitation. Water levels were manually measured at weekly intervals with an acoustic sensor.

Drainage comprised 75mm clay pipes at 9 metre spacings and 75 cm depth. The trenches were backfilled with the excavated soil. The poor quality of the land did not warrant the expense of permeable fill or a secondary treatment.

### 3.2.7 Blacklaw Moss

The study site near Lanark, in the Strathclyde region of southern Scotland, was instrumented for 5 years from 1959-64 by the Macaulay Institute and the Hill Farming Research Organisation (Robertson *et al.,* 1968). The experimental catchment is on a raised basin mire, and comprised 7 ha of upland moorland used for rough grazing. The study area was delineated by a boundary drain about 40 cm deep leading to a v notch weir with a weekly chart with a 1:1 gearing and a time scale of 1.25 mm/hr. To prevent water from entering or leaving the site at the boundary, a second ditch was cut around the site (Fig 3.11).

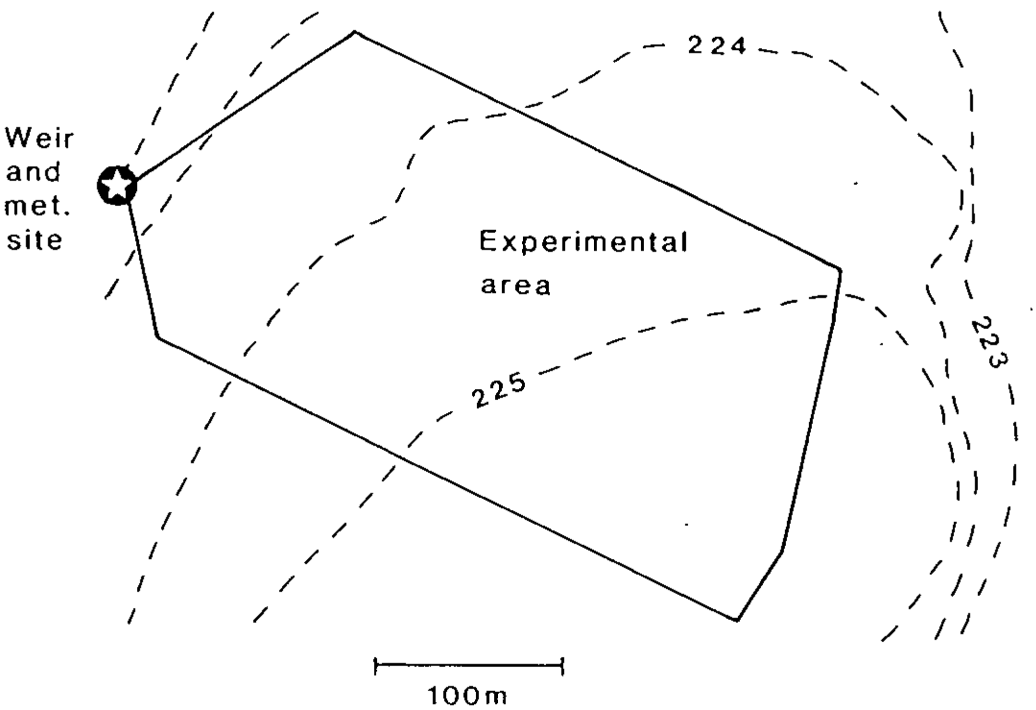



*Figure 3.11 Blacklaw Moss field drainage experiment showing the study site and instrumentation*

Rainfall was measured at a weather station on the site by a recording raingauge and a weekly check gauge. A turf wall was used to reduce catch losses due to wind effects. Potential evaporation estimates were made using an irrigated lysimeter designed by Green (1958). The water table was continuously monitored in one bore hole equipped with a water level recorder and chart recorder, and weekly manual measurements were made at two other bore holes on the site. After a 3 year calibration period the land was drained by cutting open ditches about 40 cm wide and 36 cm deep at 9 metre spacings. The climate and soils are such that more expensive pipe drainage is not warranted. Large areas of the British uplands have been drained in this way. The vegetation was dominated by heather (*Calluna vulgaris*) and cotton grass (*Eriophorum* species), with a discontinuous carpet of mosses including *Sphagnum* species.

The soil at the site is a deep peat (average depth 5.8 m) and comprises *Sphagnum-Eriophorum* peat of low to moderate decomposition becoming more highly decomposed at depth, overlying sedge-grass peat of moderate to high decomposition. A site soil profile description is given in Table 3.15. The soil is simply classed as a raised mire by the Scottish soil survey. It would belong to the Winter Hill series in the SSLRC classification, and be termed a raw oligo-fibrous peat soil. These soils are almost permanently waterlogged.

*Table 3.15 Soil profile description for Blacklaw Moss*

| Horizon | |
|---|---|
| Om (0-18 cm) | Light brown fibrous peat, comprising sphagnum moss and eriophorum (cotton grass) species of low decomposition (von Post 2) |
| Om (18+ cm) | Black peat of similar botanical origin, of moderate decomposition (von Post 4) |

NB The von Post classification of the degree of peat humification is described in many texts, including Castle et al. (1984).

## 3.3 DATA PROCESSING AND ANALYSIS TECHNIQUES

Since the data had been collected some time ago by different organisations they were not available in a computer-readable form. In most cases the data comprised the original chart records or, in the case of the soil water measurements and some of the recording raingauges, tabulated values in manuscript form.

### 3.3.1 Data processing

The chart records for all six sites were digitised at the Institute of Hydrology using digitising equipment and computer software developed from those used in the Floods Study Report project (Lowing and Newson, 1973). Due to the large amount of raw data involved (totalling 32 plot-years for the individual before, after and paired plots), chart data processing was restricted to periods covering the main storm events. All of the charts were examined and checked at the Institute of Hydrology before selecting storm periods for detailed study.

Although time-consuming this work did ensure consistent and uniform data validation and processing procedures for all the sites.

Stage levels were converted to flows using stage-discharge ratings provided by the operators. For Staylittle, Tylwch and Withernwick the rating curves were based on theoretical formulae (BSI, 1965), and for Grendon and Blacklaw Moss the formulae had been checked by volumetric gaugings. The rating for the volumetric flow gauges at Ballinamore were derived from the internal chamber dimensions supplied by the AFT. When processing the data, care was taken to check the datum level of the flow recorders on the charts and the chart gearing ratios used (relating vertical movement on the chart to changes in water levels). The chart 'on' and 'off' times were also noted, in order to correct for any timing errors in the pen movement of either the flow or autographic rainfall recorders. The maximum stage level of each weir was also noted, in order to avoid processing spurious flow values if the water level rose above the capacity of the weir. Any queries or anomalies which could not be resolved directly from the chart records were discussed with the scientists providing the data, and whose continued and active support was invaluable to this phase of the project.

In addition, the Grendon site was reopened with the same water level recording equipment that had previously been used. It was found, however, that there was a large discrepancy at both weirs between the stage levels recorded by the chart recorder and by the potentiometer and data logger. Subsequently it was learned that this difference had also been noticed in the earlier study, but the cause had not been resolved by the original operator, who had chosen the chart records in preference to the potentiometer readings after comparison with manual stage level readings. After a great deal of checking, both in the field and with the equipment removed to the laboratory, it was discovered that the potentiometers in these instruments had been incorrectly wired giving a consistent, but varying, error. This error was corrected, and all the data in this phase of the site operation were based on the synchronised rainfall and stage levels stored on a single data logger.

### 3.3.2 Data analysis

It was decided to use a standard time interval for analysis of data at all sites. In view of the likely timing accuracy obtainable from chart recorders (both stage recorders and rainfall) and the need to synchronise the two types of data, a one hour data interval was chosen as the most appropriate balance between accuracy and detail, although in some instances the raw data were actually processed at a shorter time interval.

In cases where drained and undrained catchments are adjacent, as with the Ballinamore and Grendon sites, it is simple and straightforward to directly compare the outflows for each storm event assuming, as was the case at these sites, that the paired plots were otherwise identical. The other four studies, however, comprised 'before' and 'after' comparisons, and this direct approach was not possible. Since the prevailing weather conditions varied between the periods of record and between the sites, standard measures of runoff response were necessary. The method of analysis chosen to analyse the storm rainfall-runoff relation at the different plots was the 'unit hydrograph' (see below). This technique is well suited to analysing storm event relations and is a widely used and understood method which has been adopted in many studies of catchment change (e.g. Moore and Morgan, 1969; Sangvaree and Yevjevitch, 1977; Arnell, 1989). The rainfall runoff analysis is concerned with 'direct' storm runoff; in dealing with changes in flow regimes it is also necessary to consider the effect on low flows. Low flows from the study areas before and after drainage were studied by direct comparison in the case of the paired plots and for the Withernwick site where a 'control' plot was available. For the other sites the 'master recession curve' technique was used. Soil water conditions had been monitored in a number of ways, including the water depth in dip wells and the water content of a soil profile measured with a neutron probe.

*Peak flows*

It was decided to analyse separately the rainfall runoff relationship at each of the six sites in their drained and undrained state. This was to study the impact of drainage under different catchment conditions, and to determine whether the effect of drainage at a site was constant or varied between events with, for example, storm intensity, storm magnitude or ground wetness. The shape of the discharge hydrographs will be influenced by the magnitude and time distribution of the storm rainfall causing that runoff. Thus, there could be an apparent tendency for, say, higher or faster peak flows after drainage due to chance differences between the characteristics of the storm events sampled in the two periods, such as the rainfall intensity and duration.

A method commonly used to try to remove such effects of storm differences is the *unit hydrograph*. This is essentially the characteristic response of the catchment to a unit input of rainfall (commonly 10 mm in one hour). The basic principles of unit hydrograph derivation are well known (e.g. Linsley *et al.*, 1975) and will not be repeated in detail here. In the derivation, however, there are a number of possible options - for example in the definition and separation of storm runoff, and it is necessary to outline the methods used in this study. The broad approach used follows that described in Vol I of the Flood Studies Report (NERC, 1975), but for this study a number of changes and additions were made to the procedure, and they are detailed below.

Before a unit hydrograph can be derived, it is first necessary to define the net rainfall and runoff for a storm. The procedure usually adopted is to define the net runoff by applying a certain baseflow separation in order to ascertain the amount of flow attributable to the storm rainfall as storm runoff. There are numerous arbitrary methods of defining the baseflow separation and, as noted by Newson (1975), the most important thing is to be consistent. The method used in NERC (1975) is based on that of Nash (1960) and is illustrated in Figure 3.12. Firstly the response time or 'lag' time of the catchment is defined as the delay between the centroid of the total storm rainfall profile and the stream hydrograph peak (or centroid of peaks in the case of a multi-peaked hydrograph). The pre-storm flow recession is extended by fitting a simple model based on a set of linear reservoirs in parallel, and extrapolating until the time corresponding to one 'lag' time interval following the centroid of the rain (point 'A'). This is then joined by a straight line to the falling limb of the observed storm hydrograph at a time 4 times the 'lag' time after the end of the rainfall (point 'B'). In cases for which the falling limb was interrupted prior to this, for example by another storm, it may be extended by the same curve fitting procedure used for the pre-event recessions. The resulting quantity of storm runoff thus defined is then compared with the recorded rainfall.

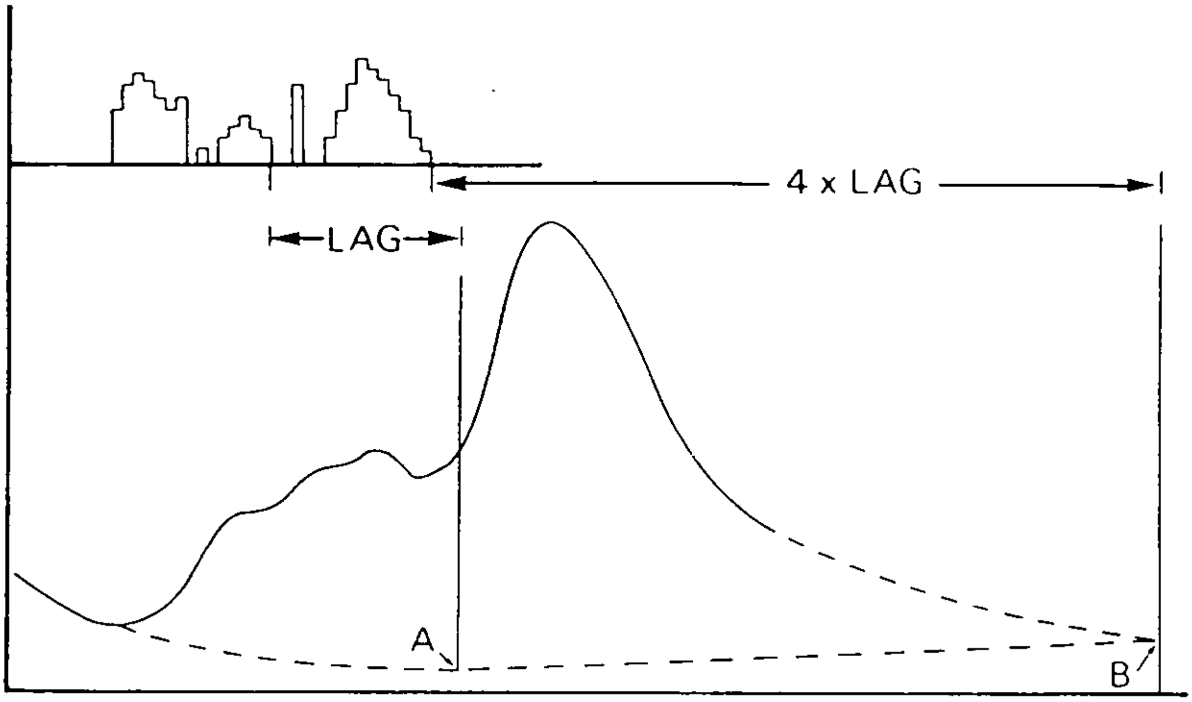



*Figure 3.12 Definition of quick reponse or net storm runoff used in the Flood Studies Report (NERC, 1975 Fig I.6.8)*

Due to 'losses' of part of the rainfall to soil water storage, interception and to evaporation, storm runoff is less than the total storm rainfall and is commonly expressed as a percentage, known as the runoff 'coefficient'. The recorded gross rainfall is reduced to a net rainfall having the same total volume as the storm discharge, by assuming either that the rainfall 'losses' are defined by a percentage of the gross rainfall, or by a certain rain intensity. Whilst certain 'physical' arguments can be applied regarding the applicability of either approach (NERC, 1975), it must be borne in mind that the total separated storm rain is in fact not calculated by physical criteria such as the available soil water storage capacity at a given time, but simply in order to 'match' the volume of arbitrarily defined net runoff. It was therefore felt that for this study there was limited value in choosing a technique on the basis of its supposed physical representation of soil water physics since any such argument is somewhat spurious. A more appropriate criterion for selection is the consistency and stability of the resulting unit hydrographs.

The unit hydrographs were derived from the net storm rainfall and net runoff, using the method of matrix inversion (e.g. Viessman *et al.*, 1972), which provides a 'least squares' fit. It is known that the most numerically stable results will be obtained from a storm rainfall hyetograph with a dominant block of net rain, rather than from a storm with a constant intensity. This is more likely to be the case for a loss rate rain separation. The percentage loss method will give a higher absolute loss in periods of high intensity rainfall, thus tending to reduce the range in net rainfall ordinates, whilst a loss rate may remove all the rainfall in periods of low intensity, leaving only a few rainfall ordinates of high intensity. The loss rate method consequently will generally give a more stable unit hydrograph and was adopted for this study.

The approach used here was a two stage process, firstly analysing events individually, and secondly comparing the average results for the different 'treatments'. In the first stage the rainfall and discharge were analysed for each storm event separately as a means of quality control. Comparing the individual storm unit hydrographs helped to identify, and eliminate from further study, events affected by snowmelt or with instrument or timing problems. The parameters of the usable unit hydrographs from such a land use change study are usually either compared directly with the changing proportion of a catchment affected by a gradual land use change, or for a rapid change they may be averaged, often graphically by eye, to provide a 'before' and 'after' comparison. In this part of the study, the comparison was of storm period flows before and after the drainage of small plots rather than of any progressive and gradual change over time in the drainage status of a large river catchment. Consequently an 'average' unit hydrograph was needed to define the drained and the undrained behaviour. The individual storm analyses were used to determine the time base of the unit hydrograph for each treatment. This was determined by taking the median of the calculated 'lag' times of the useable storms in each group, after attention had been given to cases where timing errors were suspected.

Since graphical averaging of the unit hydrographs derived from individual events is necessarily subjective, an automatic method which was both straightforward and objective was thought to be much more appropriate. Several methods have been proposed for the joint analysis of a number of events to produce a single average unit hydrograph (e.g. Diskin and Boneh, 1975; Bree, 1978). For this study a method which has been termed 'superposition' (Boorman and Reed, 1981) was selected as being both simple and objective. The unit hydrograph method assumes that the relation between the net rainfall and runoff is linear and time invariant (e.g. Dooge, 1973). Accordingly, the net rainfall profiles for a number of storm events were added together (superposed) to make one 'super' storm rainfall profile, and the corresponding net runoff hydrographs were also added together to make one 'super' storm runoff hydrograph (Fig 3.13). The storm data were combined to align the peak blocks of net rain. The superposed net rainfall and runoff were then used as the input to a standard unit hydrogaph derivation program using the matrix inversion method to derive a single unit hydrograph. The unit hydrograph derived in this way is therefore an 'average' of all the component storm runoff responses, and has the advantage over the conventional averaging of individually derived unit hydrographs of giving more weight to events with a greater net storm runoff, whilst the latter method averages unit hydrographs irrespective of their event size. Furthermore, the average unit hydrograph derived by this technique is usually well-conditioned (stable) and does not require further smoothing. In contrast, the NERC (1975) procedure, for example, uses a moving average and the addition of 6 leading and 10 trailing

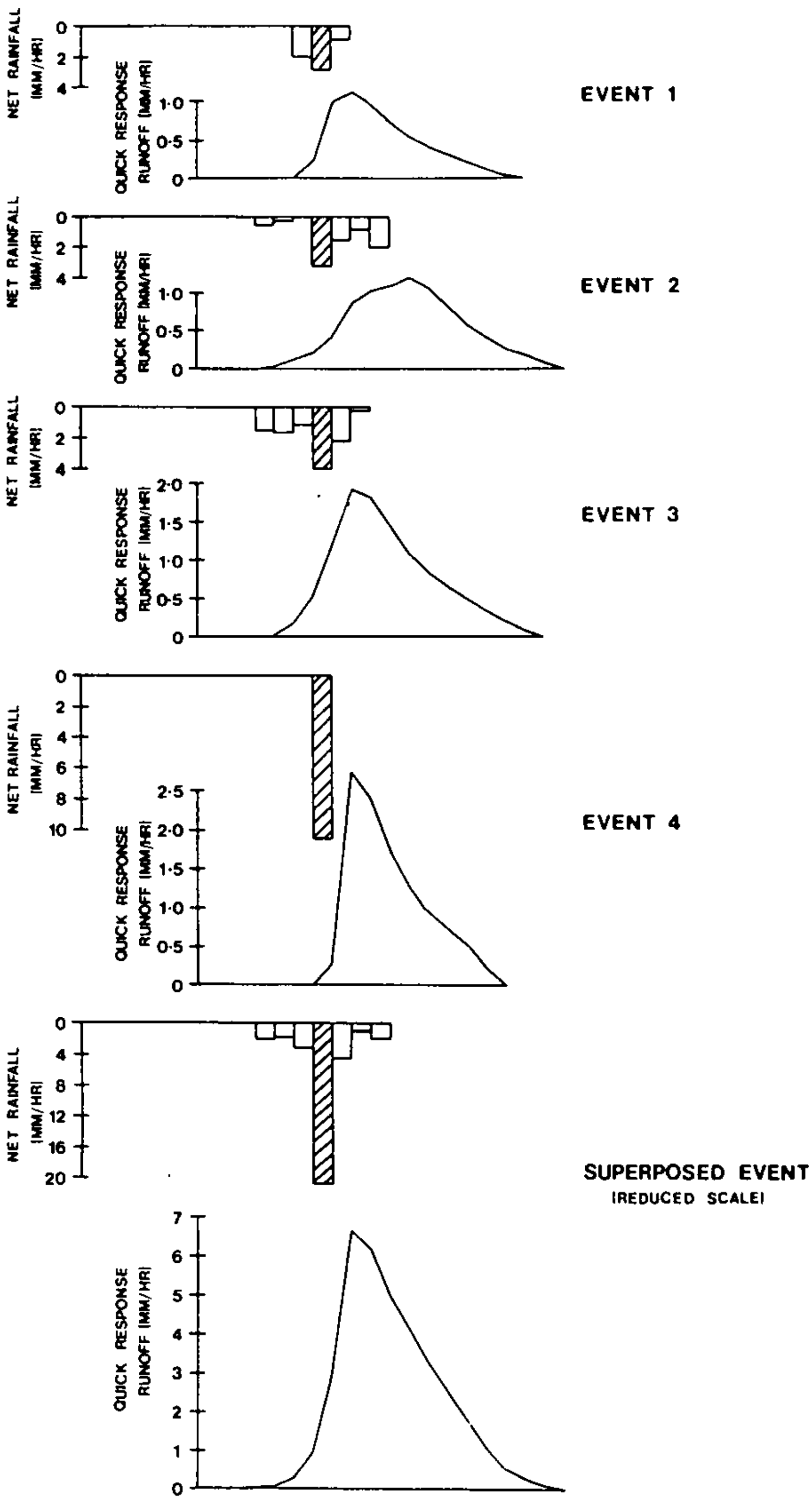



*Figure 3.13 Derivation of an average unit hydrograph by event superposition*

zeroes to give a fixed amount of smoothing to the derived unit hydrograph, irrespective of its degree of stability.

This technique was used to obtain an average unit hydrograph for each catchment/treatment. These provided a means of quantifying and comparing the runoff response of drained and undrained land (and comparing differences between different sites). Summary parameters of the individual storm unit hydrographs (such as the time to peak flow, and the peak hourly ordinate) were used in statistical tests of the difference in response of each site under the drained and undrained conditions. The results are discussed in Chapter 4.

*Low flows*

At sites where flows from drained and undrained land are collected and measured in the same manner, and under the same weather conditions, they may be directly compared. This was not, however, generally the case for the low flows at the study sites. There were differences in the depth to which flows were intercepted from the paired plots at both Grendon and Ballinamore. Whilst these differences would not have a significant effect on storm period peak flows, they may have affected the recorded low flows. Measures of low flows are also very sensitive to the duration of dry weather periods, and the records at three sites (Tylwch, Staylittle and Withernwick) included the severe drought in 1976.

The principal method of analysis of low flows used in this investigation is based on the rate of recession or decline of flows on the falling limb of the hydrograph, after the end of storm rainfall. The recessions for a number of storms may be plotted together and a 'master recession curve' drawn (Wilson, 1983; Shaw, 1988). The lower sections of the falling limbs of stream hydrographs are plotted on a logarithmic flow scale with a linear time scale. Starting from the lowest flow a curve is drawn tangential to the lower portions of the individual curves (Fig 3.14).

These curves may be derived from storm recessions before and after drainage and then compared, to study the effect of drainage on low flows. Care must be taken, however to compare recessions occurring under similar weather conditions; not only should the recessions be from rainless periods, so that the flows represent the rate of depletion of water stores in the catchment, but also the evaporative demand should be similar; Weisman (1970) for example, noted steeper streamflow recessions in summer than in winter, since in summer the evaporation losses were greater and soil water reserves were lower.

*Soil water conditions*

Soil water conditions in the drained and undrained land were monitored at all the sites. This was important in order to understand the within-field processes that were responsible for the observed differences in the outflows. It has been argued (Trafford, 1973; Bailey and Bree, 1981) that soils with a large drainable porosity will exhibit a large increase in the available water storage capacity after drainage which will act as a 'buffer' to absorb storm rainfall, and consequently result in reduced peak discharges. Whilst the methods of measuring rainfall and flows were reasonably similar at the six sites (apart from the cumulative flow recorder at Ballinamore), the measurement of soil water conditions varied greatly between sites including the use of dip wells, tensiometers and a neutron probe (Table 3.3).

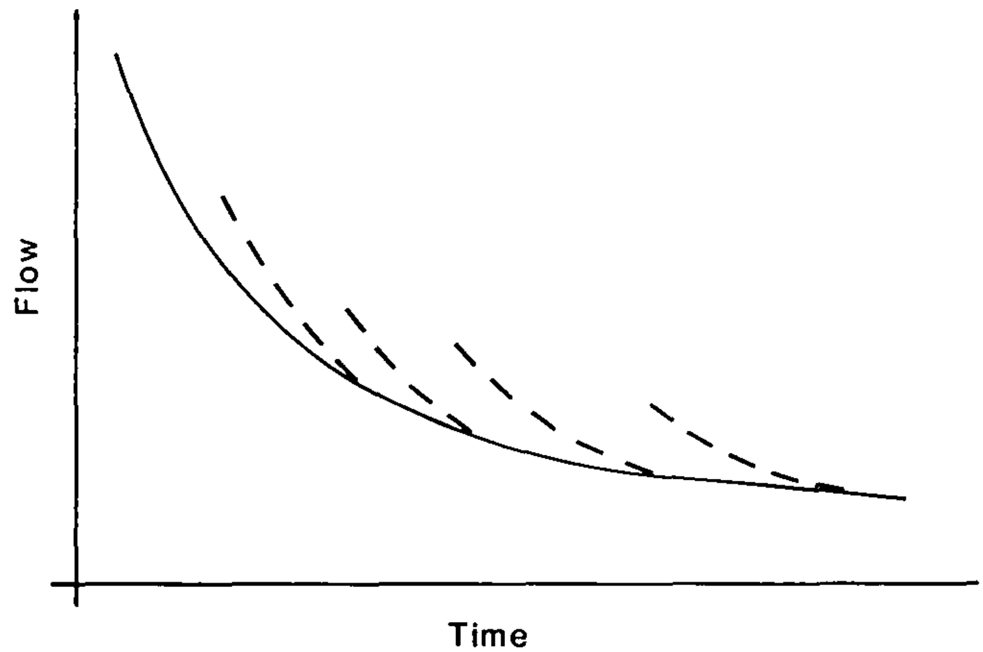



*Figure 3.14 Construction of a master recession curve from a number of storm recessions*

Unlined dip wells are the simplest and cheapest method of studying soil water regimes. They provide information on how long, and how high up the profile waterlogged conditions persist. They are often described in the literature as recording the depth of the 'water table' although this is somewhat misleading since the the 'free water' in the soil may often be a local perched water table, independent of the deeper mass of 'regional' groundwater. Whilst in theory the water level in a bore hole should be the same as the level of zero water potential in the soil, this may not be the case in practice due to the 'reservoir' and 'bypass' effects (Hinson *et al.*, 1973).

The 'reservoir effect' may be important in soils of low permeability in which there is a long time lag between changes in soil water potentials and changes in dip well water levels. This time lag increases with the diameter of the dip well and as the hydraulic conductivity of the soil considered gets smaller. The lag may be estimated by bailing out water when there is no rapid natural change occurring, and timing the recovery of the water level. For a given soil the reservoir effect may be minimised by using a small diameter bore hole (Harris, 1977).

The 'bypass effect' occurs in soils with profiles containing horizons with different permeabilities. In these situations the bore holes may provide a flow route for water between horizons. Thus, for example, if a soil has slowly permeable surface layers overlying more permeable horizons, the bore hole may allow water from the surface to drain directly to the lower layers. The reverse situation could occur where water in lower layers is under 'artesian' pressure. The effect of soil layering will become apparent if water levels differ in adjacent bore holes which are of different depths (and hence cut into different horizons). The use of a bore hole treats the whole soil profile as a lumped entity and it is therefore important to note the soil properties as the soil is removed from the auger hole, or to dig a soil pit, in order to try to understand the profile's drainage characteristics.

Tensiometers largely eliminate these problems and also provide information on conditions in the unsaturated zone, including the extent of capillary rise above the water table. They are, however, more difficult to operate and expensive than dip wells. They cease to function when soil water potentials fall below 80 kPa (800 cm suction) due to air entering the system, and this needs to be 'purged' and replaced by unaerated water. There are also sampling problems in clay soils since even adjacent tensiometers may give very different readings depending upon whether the ceramic cup is situated in a soil ped or in a crack or fissure.

Neutron probes are widely used to measure soil water contents. They measure the water content in a sphere which varies in radius with the soil water content from about 10 cm in wet soil to 25 cm in dry soil. Consequently they do not measure changes near to the ground surface, and do not distinguish abrupt changes in water content at soil horizon boundaries.

## 3.4 SUMMARY AND CONCLUSIONS

Data were obtained from six sites in the British Isles where flows had been measured from undrained and drained land. The sites were all inspected in the company of scientists closely involved with their operation, and the sites had to meet certain criteria before being included in this study. The 'raw' data were carefully examined and 'quality controlled'. The data were then processed in a completely consistent and uniform manner prior to analysis. Information about site characteristics, such as soil properties and artificial drainage parameters, were obtained. The range of drainage types studied was fairly restricted, but nevertheless the types of schemes are very typical of the predominant drainage work in Britain in recent years. Similarly the soils studied represent only a small range of all possible soil types, namely low permeability soils with a 'surface water' problem, but these are typical of the main areas drained. Thus the findings from these sites should have widespread, if not universal, application.

# 4. Field experimental results

## 4.1 INTRODUCTION

The plot studies described in Chapter 3 were then analysed in a uniform manner. This chapter is concerned primarily with the changes in the storm response, but low flows and soil water conditions are also discussed. The storm data are summarised in a number of tables, using the following notation:

Qmax Maximum flow peak of storm hydrograph (mm/hr)

Rtot Total rain in storm (mm)

Rmax Maximum hourly rain depth (mm)

%RO Storm runoff coefficient : (net runoff/Rtot) * 100%

The one-hour average unit hydrographs are summarised by:

Tp Time to peak ordinate (hours)

Qp Peak ordinate (as a proportion of the total flow)

N Number of storm events analysed

It is useful to note that the conversion factor between the two most commonly used methods of expressing specific discharge is :

1/s/ha x 0.36 = mm/hr

## 4.2 CHANGES IN FLOWS AT THE STUDY SITES

The processed data from the study sites were first analysed individually for the undrained and drained 'condition' and the effect of drainage on flows was determined for each site. The results are then compared and differences interpreted in terms of site characteristics. Finally, readily available criteria are proposed to distinguish in advance of any drainage those areas where such work will increase peak flows downstream.

### 4.2.1 Ballinamore

The response times of the two small plots were so short that the hourly data interval gave only one or two data points on the rising limb of the storm hydrograph. This was felt to be too coarse for unit hydrograph analysis, although adequate for direct comparison of the plot outflows. The use of a shorter data interval was considered to be unrealistic, given the mechanism of the cumulative flow recorders.

In the 10 month 'calibration' period before drainage, the amount and timing of outflows from the two plots were very similar, confirming the uniformity of the site (Fig 4.1). Small differences in storm flows were within the likely error bounds of digitising the cumulative flow charts. Since the rates of flow are represented by the slopes of the chart traces, any errors in digitising or any timing errors would directly influence the flow rates. There was no statistically significant difference between the plot outflows over this period in the timing or magnitude of a sample of 10 large storm peak flows averaging 1.7 mm/hr maximum hourly flow rates. There was a small but systematic difference between the low flows from the two plots in the calibration period prior to drainage. Dry weather flows were slightly higher from the 'control' plot, probably due to a small difference in positioning the surface flow collectors.

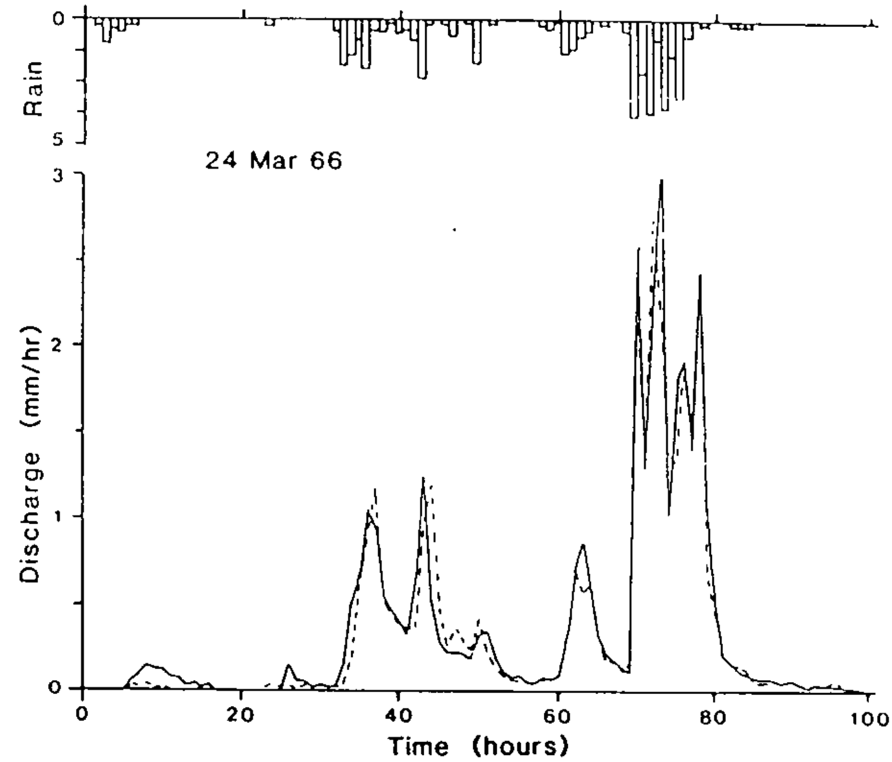



*Figure 4.1 Comparison of storm runoff hydrographs from the two experimental plots at Ballinamore in the initial calibration period, prior to drainage*

Following drainage there was a clear difference between the storm flows from the two plots. Figure 4.2 shows a typical sequence of storm hydrographs in the first winter. Maximum flows from the drained plot were consistently lower than from the undrained land, despite the possibility of unmeasured interflow from the latter below the 10 cm surface root mat layer (Fig 4.2a). This pattern was repeated in each of the following five winters studied (Fig 4.2b). Recession period flows, however, were higher from the drained than undrained land, so that the total measured flows were similar (e.g. 71% and 76%

respectively of the rainfall for Fig 4.2a, and 70% and 73% for Fig 4.2b). The mole drainage largely eliminated topsoil saturation and there was negligible surface layer flow; in the five year period, from November 1966 to October 1971 inclusive, there was an annual average of 342 mm surface layer flow from the undrained plot, but only 34 mm from the drained plot (much of this was in the final two years of the period when the mole drains may have begun to deteriorate).

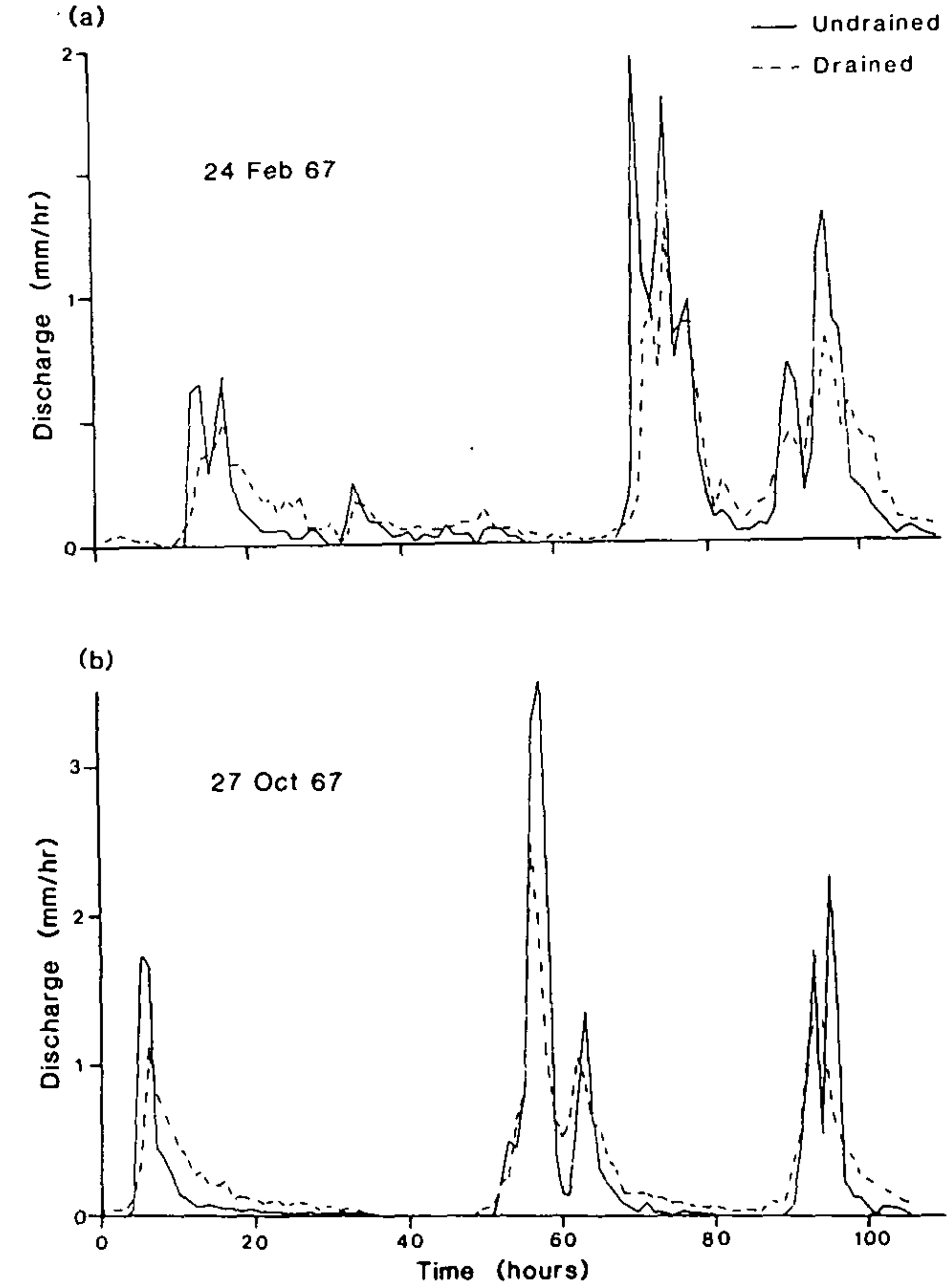



*Figure 4.2 Comparison of storm hydrographs from the drained and undrained plots at Ballinamore in a) first winter after drainage b) subsequent winter*

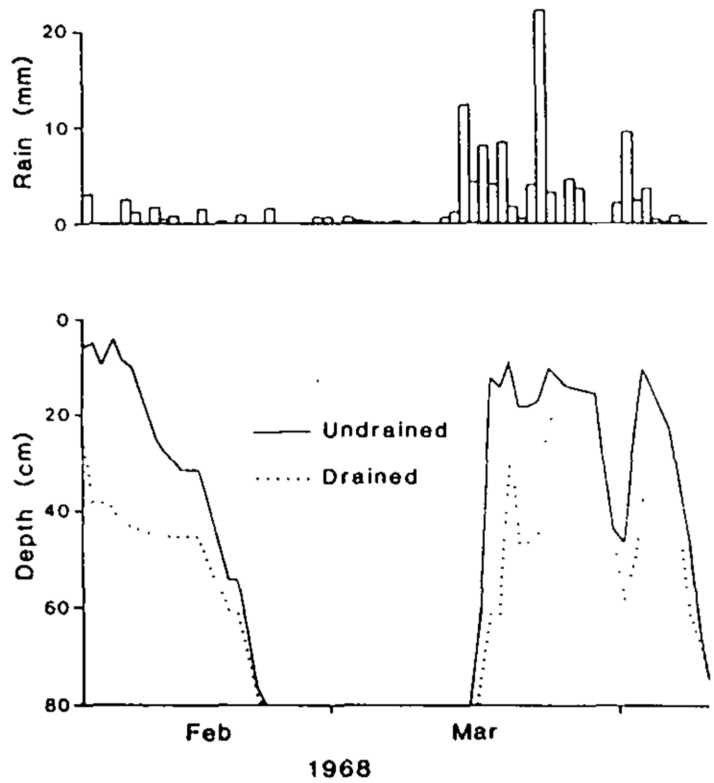



*Figure 4.3 Tensiometer data indicate the position of the water table on drained and undrained land at Ballinamore.*

The effectiveness of the mole drains in controlling soil water conditions was shown by the tensiometer data (Fig 4.3). The water table was within 20 cm of the ground surface for long periods in winter, whilst on the drained plot, even mid-way between the moles it was rarely less than 40 cm deep.

The evidence indicates contrary to the fears expressed by Trafford (1973) that mole drainage of clay soils would increase peak flows, its effect was in fact to reduce peak rates of runoff through the increased potential water storage capacity of the drier soil. This, in turn, resulted in an enhanced rate of runoff between storms. Due, however, to the differences in the depth of collection of flows, the effect of drainage enhancing low flows cannot be strictly quantified.

Flows from both drained and undrained plots ceased for several months each summer, but when they resumed in the autumn it was apparent that for a period of several months the relative values of the peak flows from the two plots had reversed - the drained plot yielding higher maximum flows and total flows (Figs 4.4a, and 4.4b). Total flows in these periods shown amounted to 19.5 and 27.0 mm for the undrained and drained land respectively in Fig 4.4a (due to a fault in the rainfall recorder they cannot be expressed as a percentage of the rainfall). For the period in Fig 4.4b, the flows represented 46% and 72% of the rainfall. Low flows continued to be higher from the drained plot.

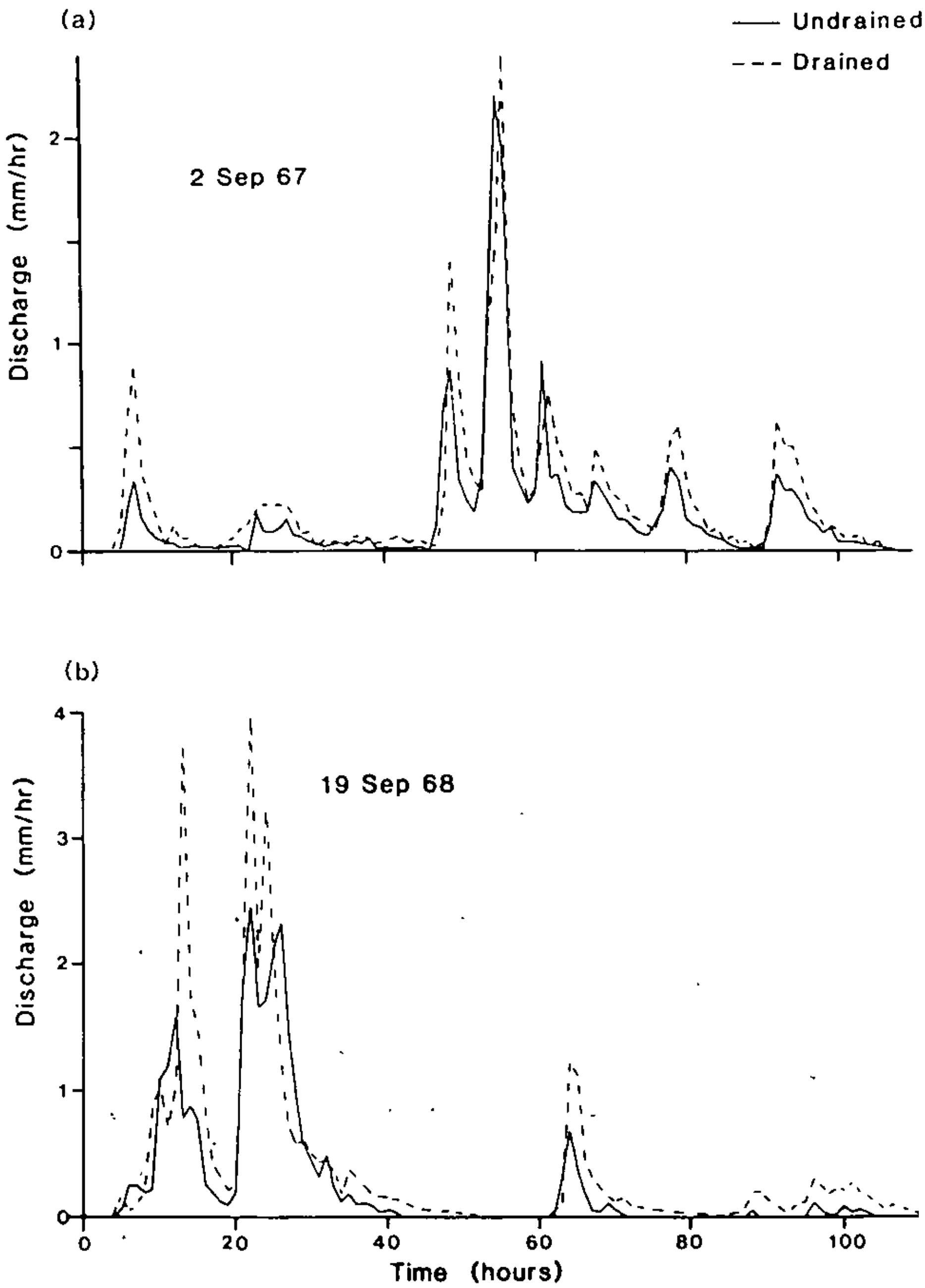



*Figure 4.4 Comparison of storm hydrographs from the drained and undrained plots at Ballinamore in a) summer 1967 and b) summer 1968*

When the difference in the peak stormflows from the two plots are considered in the context of the time of year, there was a very clear seasonal pattern (Fig 4.5). For nearly 70 storms studied it was found that with little exception the events from late October to May had lower peaks from the drained land, whilst the converse was true from June to September (Robinson *et al.,* 1987).

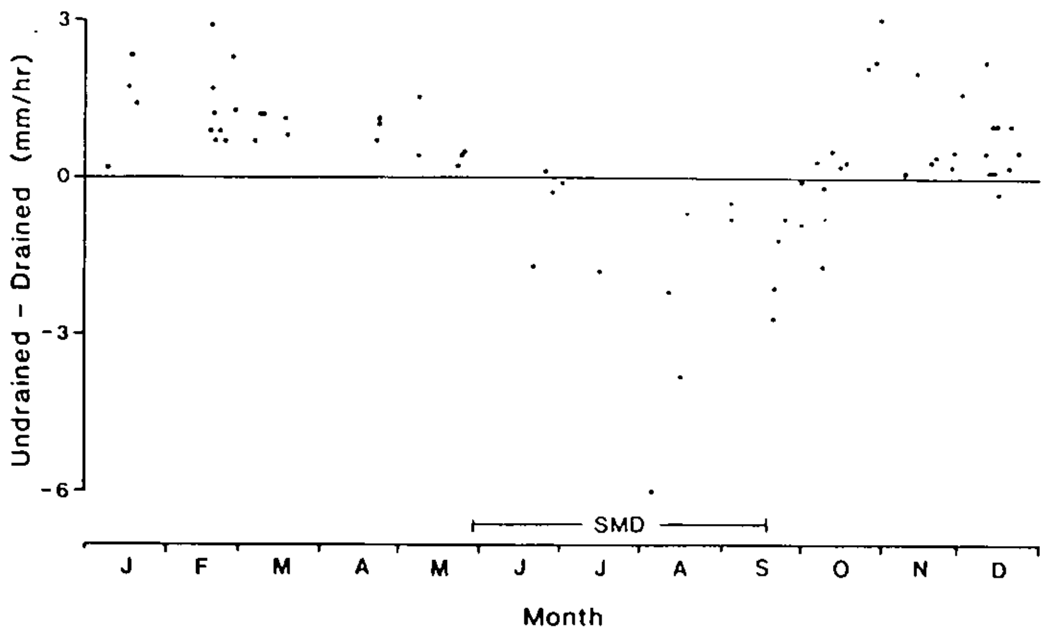



*Figure 4.5* ***Seasonal pattern of differences (mm/hr) in storm hydrograph peaks at Ballinamore (undrained minus drained). The drained land has lower peak outflows in winter and higher peaks in summer.***

The mechanism accounting for this seasonal change in the relative behaviour of the plot outflows was attributed to the role of bypass flow through soil macropores. At Ballinamore in summer, the formation of shrinkage cracks allows rapid 'short circuiting' of flows from the surface to the mole drains, bypassing the soil matrix. This mechanism is particularly effective in periods of intense rain (Fig 4.6).

Burke *et al.* (1974) calculated the aggregate hydraulic conductivity for the soil profile above the mole drains was about 3.1 cm/hr in May 1967. This is four orders of magnitude greater than the subsoil (matrix) conductivity measured from a small soil core, and this difference reflects the movement of water through cracks and fissures. In the autumn these cracks begin to narrow down as the clay soil peds swell up with increasing moisture content, and saturation of the surface layers of the undrained plot resulted in higher storm peak flows than from the drained plot. This change in response over the course of the year, not previously noted by other researchers, accounts for the contradictory interpretations of the data by Burke *et al.,* (1974) and Rycroft and Massey (1975). Although each year shows the seasonal behaviour indicated in Fig 4.5, there are differences in detail due to differences in the amount and distribution of rainfall.

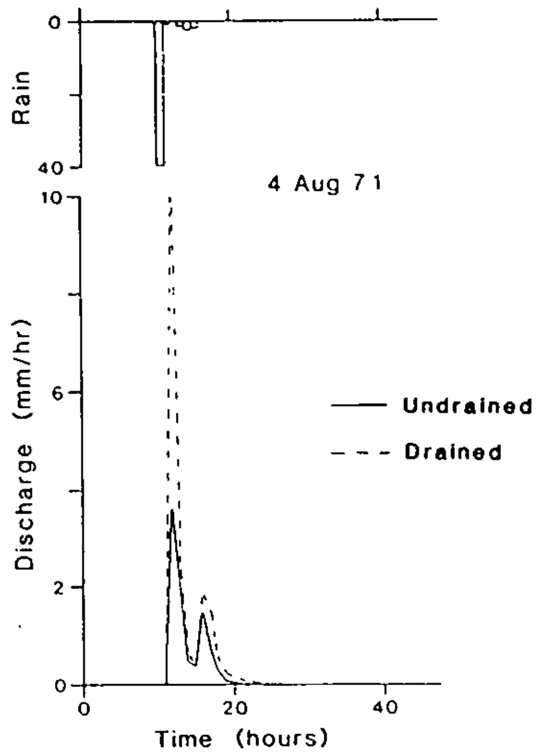



*Figure 4.6 Comparison of the outflow hydrographs from drained and undrained land at Ballinamore due to a very intense storm on dry ground in August 1971*

Over the study period it was evident that dry weather flows tended to be greater from the drained plot than from the control. This was despite the fact that the latter plot had yielded the larger low flows in the calibration period, and suggests that drainage had increased the rate of loss of water from the soil, between storm periods. The observed increase was not large, however, and although flows from the drained plot continued for longer after the cessation of rain than from the undrained control, they still ceased for long periods in summer. This apparent increase in low flows must, however, be qualified by the difference between the plots in the depth to which outflows were collected and measured.

### 4.2.2 Grendon Underwood

Data were collected over four winters, with direct comparisons possible between the outflows from the two plots. It was noticed that sometimes one plot gave the higher storm peak, and sometimes the other, but there was no clear pattern (Beven, 1980). With the collection of further data for this study, the number of storms recorded was greatly increased, and it became possible to look for factors responsible for the variable effect (Robinson and Beven, 1983). The most important factor was found to be the ground wetness, and when the data were divided on the basis of the calculated soil moisture deficit there was a clear tendency for higher storm flows from the undrained plot in winter (zero SMD) (Fig 4.7), and lower peaks from that plot in summer (Fig 4.8).

Ideally, direct measurements of soil water content would have been used, but these data were not available prior to many of the storms. Surface saturation tubes demonstrated the saturated state of the topsoil in the undrained plot for long periods in the winter. This was confirmed by the neutron probe data which indicated profile soil water contents up to 10-20 mm lower on the drained plot (Beven, 1980).

The largest storm events in the period of record were divided on the basis of the SMD and are summarised in Table 4.1, using the notation specified in Section 4.1. This clearly demonstrates the seasonal difference in peak flows, with higher observed discharges from the undrained plot in winter, and from the drained plot in summer. Both plots exhibit peakier unit hydrographs in summer (with shorter Tp and higher Qp values), as a result of seasonal shrink-swell of the clay soil. The difference in storm flows was especially marked for the drained plot. In summer, bypass flow through the cracks can quickly reach the mole drains, giving a rapid flow response and also a higher runoff coeficient. In contrast, in the undrained plot there is no such exit route from the base of the soil crack system, and much of the water is imbibed into the soil peds and will go to reduce the SMD. In winter, the undrained plot yields the higher runoff peaks and volumes due to the saturation of the soil.

*Table 4.1 Comparison of storm runoff events at Grendon*

| (Winter) | Qmax | Rtot | Rmax | %RO | | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| Undrained | 0.27 | 5.0 | 3.2 | 28 | : | 3.0 | .13 | 9 |
| Drained | 0.18 | 5.0 | 3.2 | 23 | : | 3.5 | .11 | 9 |
| (Summer) | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
| Undrained | 0.18 | 5.5 | 4.0 | 19 | : | 2.0 | .23 | 5 |
| Drained | 0.49 | 5.5 | 4.4 | 26 | : | 2.0 | .31 | 5 |

It was noted from the observed hydrographs that baseflows were higher from the drained plot, indicating that drainage increased low flows. The amount of the increase may have been enhanced, however, by the deeper collecting drain (90 cm cf 30 cm on the undrained plot).

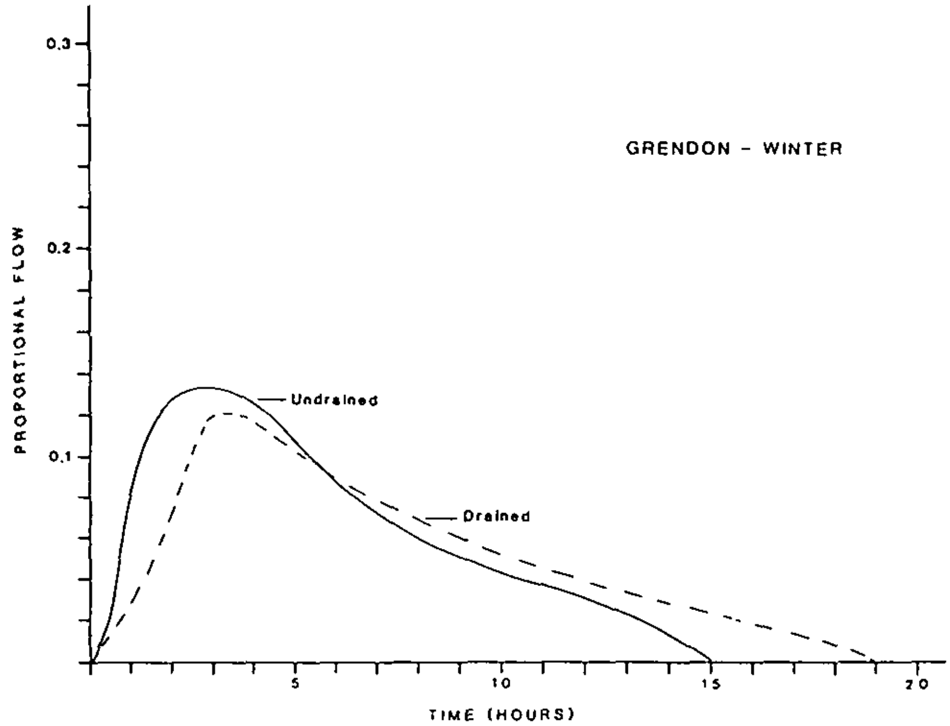



*Figure 4.7* *Comparison of one-hour average unit hydrographs for drained and undrained land at Grendon for winter storms with wet antecedent conditions*

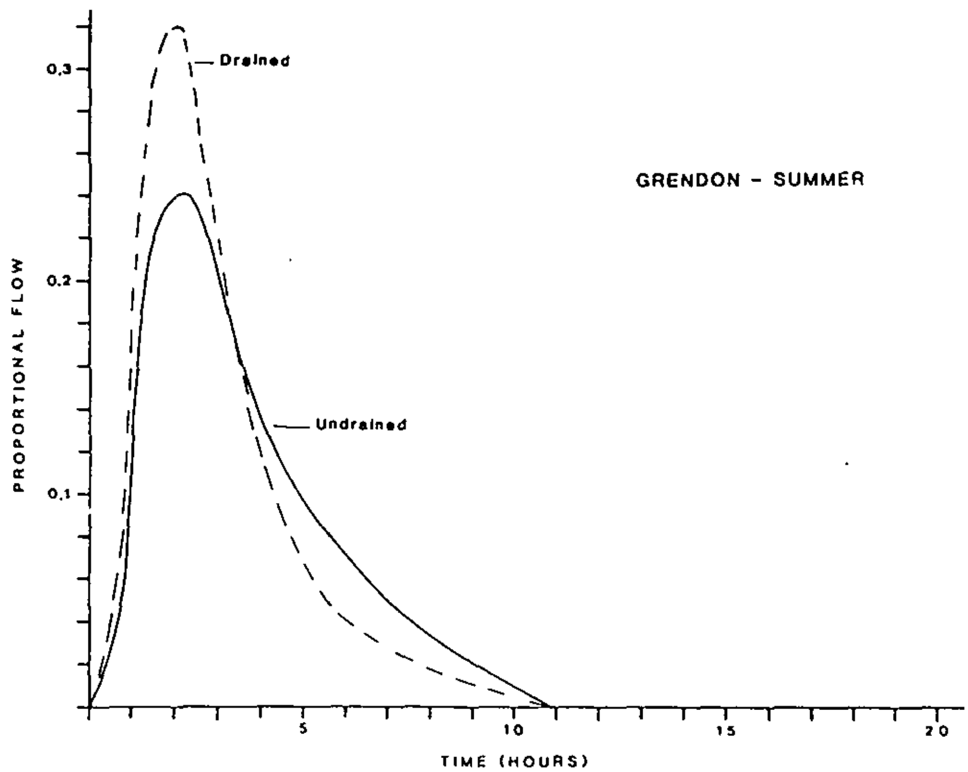



*Figure 4.8* *Comparison of one-hour unit hydrographs from drained and undrained land at Grendon for summer storms on dry ground (SMD > 5 mm)*

### 4.2.3 Tylwch

The measurement period of this 'before' and 'after' study comprised about 10 months (Oct 1975 - Aug 1976) prior to drainage and 11 months (Sept 1976 - July 1977) after drainage. The five largest storms in each period were analysed and the average values of storm rainfall and runoff parameters are given below. Although the storm rainfalls and maximum intensities were slightly higher in the period after drainage, the peak outflows were actually much lower. This was the result of both lower unit hydrograph peaks and lower runoff coefficients (Table 4.2).

*Table 4.2 Comparison of storm runoff events at Tylwch*

| | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| Before | 1.17 | 15.3 | 4.4 | 52 | : | 2.0 | .32 | 5 |
| After | 0.66 | 16.3 | 5.3 | 29 | : | 2.5 | .13 | 5 |

There was no tendency for the unit hydrograph parameters to vary with storm characteristics or season, so an average unit hydrograph was derived for storms occurring before and after drainage (Fig 4.9).

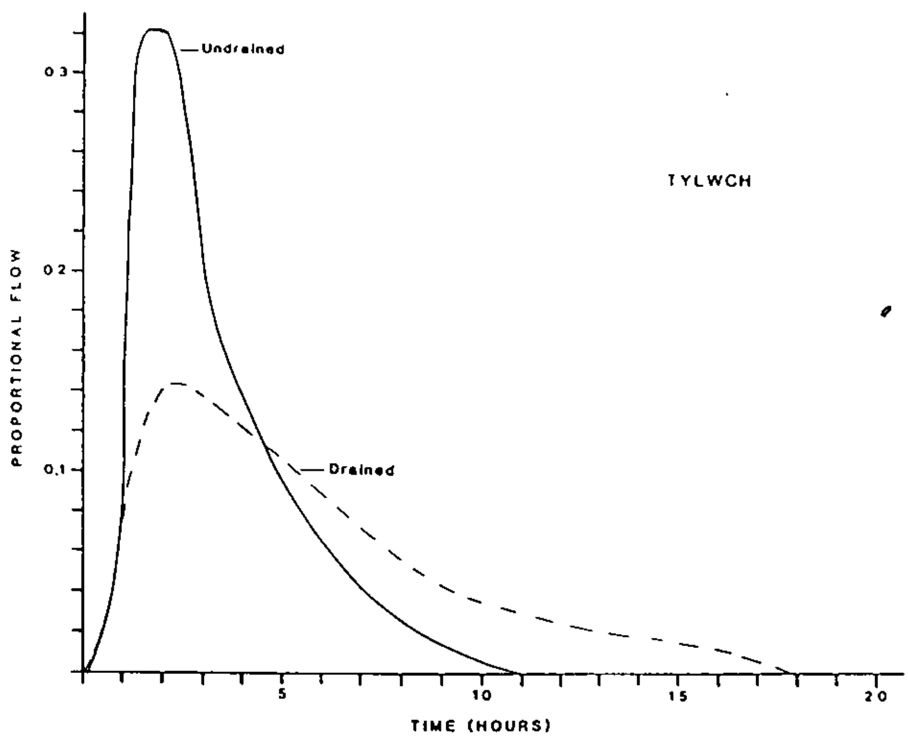



*Figure 4.9 Comparison of one-hour average unit hydrographs for periods before and after drainage at Tylwch*

After drainage there was an apparent reduction in peak flows, with a smaller runoff coefficient and a change in the unit hydrograph peak to a longer, lower, response. In interpreting these results it should be noted that the drainage took place in the summer of 1976, and the post-drainage responses may have been affected by the severe drought in that year. In particular this may have affected the rainfall losses, and reduced the storm runoff coefficients. Although all the studied events had a calculated initial SMD of zero, actual deficits may have been much greater (Newson, 1980). The rainfall in June to August inclusive was only 50 mm (cf 1941-70 average of 275 mm), and for the Plynlimon region the drought had a return period of over 100 years (Newson, 1980). Rainfall in the autumn of 1976 was only about 85% of the average, and only reached average falls in the winter. The drier weather after the drainage may also be reflected in the master recession curves for Tylwch, which unlike those at all the other sites showed no increase in dry weather flows after drainage (Fig 4.10).

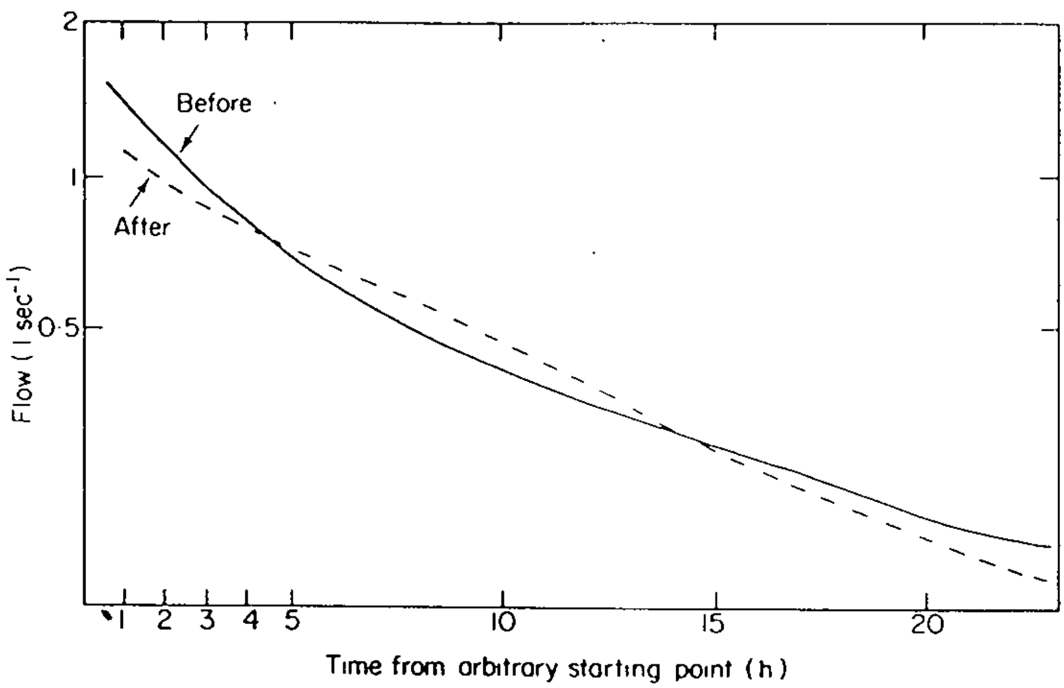



*Figure 4.10 Comparison of master recession curves for Tylwch, before and after drainage*

The dip well data showed that before drainage the water table was within 40 cm of the surface for an average of 41% of the time (and for over half of the time at 4 of the 11 wells). This may be compared with an average of 19% of the time after drainage (and only near the surface for over half the time at only one dip well). This difference, however, is also likely to have been influenced by the occurrence of drier weather in the post-drainage period (Newson and Robinson, 1983).

## 4.2.4 Withernwick

The study period comprised nearly 7 months (January 1974 to July 1974), before the main period of drainage and 19 months (August 1974 to March 1976) afterwards. The rainfall and resulting flows to the main weir 'B' for the largest events are summarised in Table 4.3.

*Table 4.3 Comparison of storm runoff events at Withernwick*

| | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| Before | 0.10 | 6.0 | 2.6 | 15 | : | 5.0 | .09 | 3 |
| After | 0.17 | 6.8 | 3.2 | (15) | : | 4.0 | .18 | 5 |

Drainage reduced the unit hydrograph peak and lengthened the response time. The runoff coefficient was unchanged but this may have been affected by the dry weather in the study period after drainage, and the resulting drier soil. At the 'control' catchment to weir A the average runoff coefficent for the same storms was halved between the two periods from 30% to 14.5%. Since this reduction could not have been influenced by the installation of the drains in the fields downstream, and no land use changes occurred in this catchment, it must represent the consequence of differences in weather conditions. Thus when the storm flows from the drained catchment are compared with those at the control weir for the two periods it appears that there probably was an increase in the percentage runoff due to field drainage.

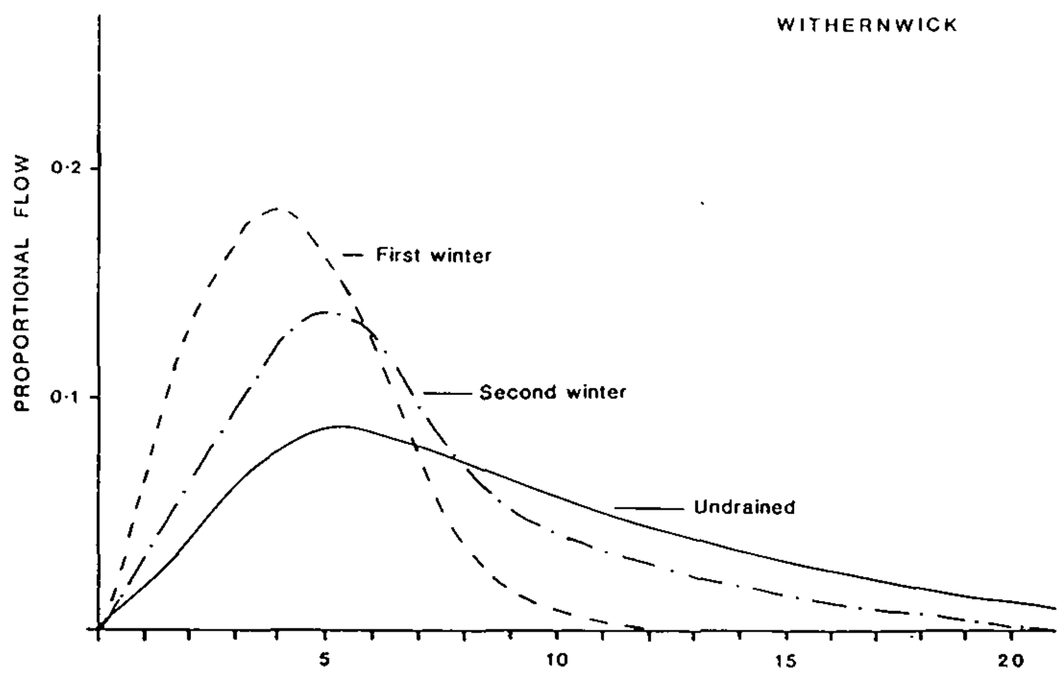



*Figure 4.11 Comparison of one-hour unit hydrographs, before and after drainage at Withernwick*

The increase in effectiveness of the drainage in removing storm flow is illustrated by changes in the unit hydrographs over the study period (Fig 4.11). The increase in peak flows was higher in the first winter (1974/5), following 56% of the area being drained in the preceding summer, than in the following winter when a further 19% was drained. This indicated that the secondary drainage treatment of subsoiling was of very short-term effectiveness at this site (Robinson, 1987). This conclusion is confirmed by local practice; the farmer repeats the subsoiling of his land every two years.

Unfortunately the records for the weir on the single outfall drain of field 2, which could have allowed this phenomenon to be studied in more detail were unsuitable. This was due to the frequent backing up of water from the outfall ditch in storm periods caused by the presence of the main weir 'B' structure.

Low flows could be directly studied by comparing flows at the control weir and the main weir. Stage values were taken from the weekly gauge board readings made when the charts were changed, as these were felt likely to be the most reliable measurements for low flows. The low flows recorded by a v notch weir are proportionally much more sensitive to errors in stage readings than higher flows, and may be affected by factors such as leaves or other debris blocking the weir notch. It was assumed that any such blockages would have been removed when the charts were changed, giving a true reading of the water level. Comparison of flows for the six-month calibration period in early 1974 (when only 25% of the experimental area was drained) with those a year later when a further 56% was drained (i.e. 81% in total) showed a clear increase in baseflows due to drainage (Fig 4.12) (Robinson *et al.*, 1985).

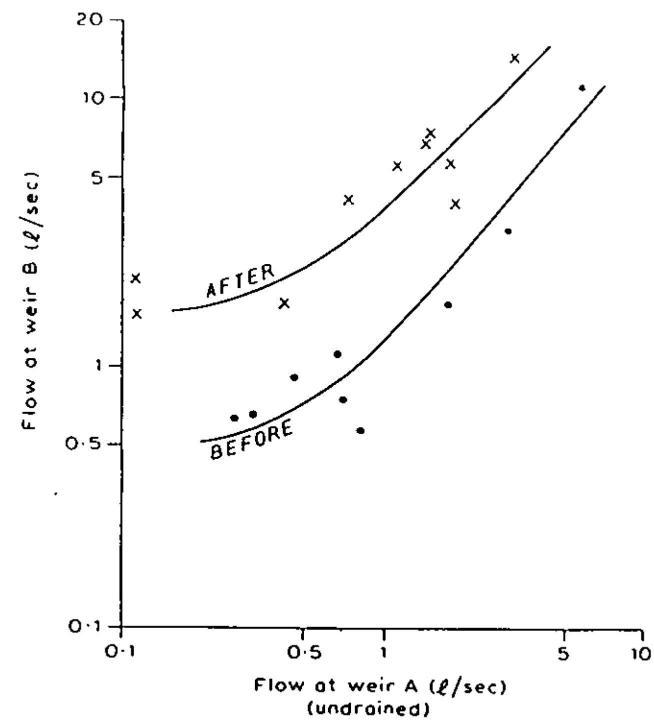



***Figure 4.12 Increase in dry weather flows at Withernwick as the percentage of the study area artificially drained was increased from 25% to 56%***

Soil water levels were continuously recorded in two dip wells; one at mid-drain spacing in field 2, the other on undrained land in field 4. Data for a six-month period from December 1974 to June 1975, before the drainage of field 4, are shown in Figure 4.13. This indicates that the water table in the undrained land was 40-60 cm below the ground surface for much of this time, whilst at the drained site it was generally 10-15 cm deeper, and only rarely within 50 cm of the surface (the approximate depth of the subsoiling).

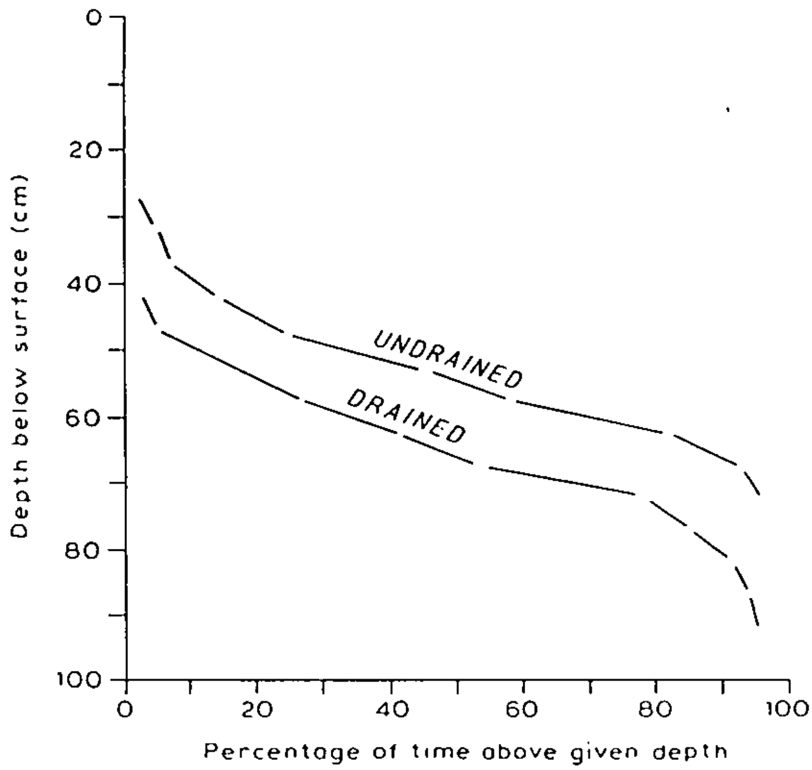



*Figure 4.13* ***Soil water levels in drained and undrained land at Withernwick***

## 4.2.5 Staylittle

The study period comprised about 16 months (Nov 1975 - March 1977) before drainage and about 12 months (April 1977 - March 1978) after drainage. The largest storm hydrographs in each period were selected for analysis and average values of the rainfall and runoff parameters are given in Table 4.4.

*Table 4.4* ***Comparison of storm runoff events at Staylittle***

| | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| Before | 1.44 | 30. | 5.6 | 25 | : | 2.0 | .23 | 4 |
| After | 1.42 | 41. | 7.2 | 27 | : | 2.5 | .14 | 9 |

There was little difference in the average observed peak flows, despite the storm rainfall being somewhat larger and of higher intensity in the period after drainage. Drainage lowered the unit hydrograph peak and lengthened the response time (Fig 4.14), but there was little apparent change in the storm runoff coefficient.

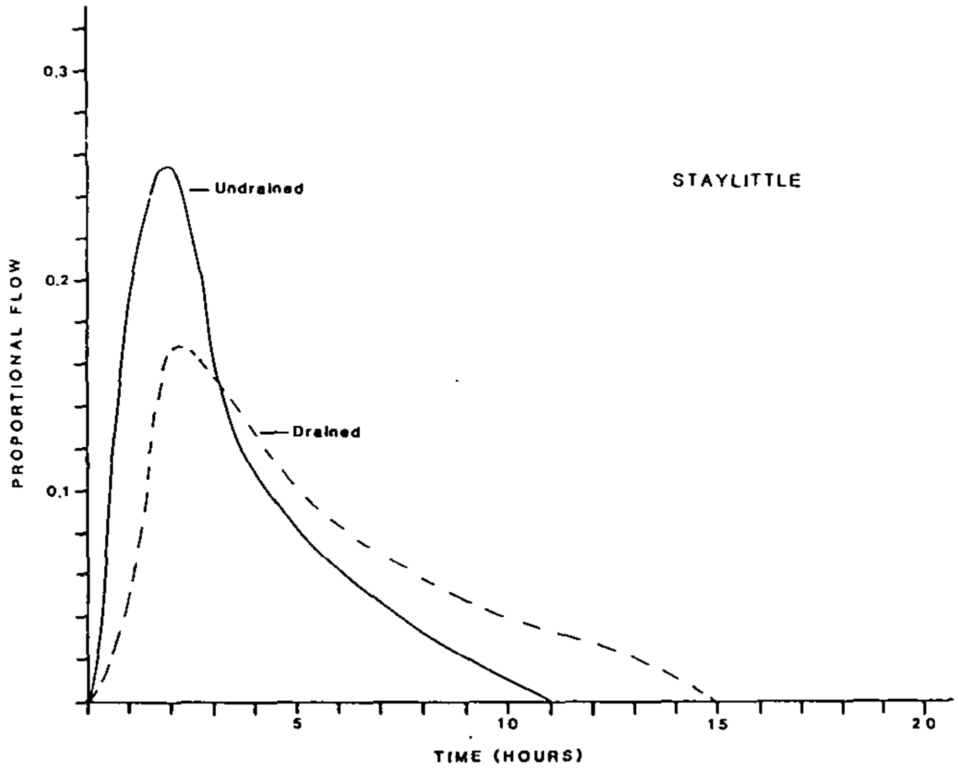



*Figure 4.14 Comparison of one-hour average unit hydrographs for storm events before and after drainage at Staylittle*

The impact of drainage at this site was not so confounded with the effect of the 1976 drought as at nearby Tylwch due to the different study period. The master depletion curve at Staylittle showed a clear tendency for a slower rate of recession, and hence higher baseflows after drainage (Fig 4.15). Data from the 14 dip wells indicated that before drainage the water table was within 40 cm of the ground surface for 68% of the time (i.e. a much wetter site than Tylwch). After drainage the average fell to 31% of the time. There was a clear difference between the main soil types at this site in the effectiveness of the artificial drains in lowering the water table (Newson and Robinson, 1983). There was a much more limited reduction in the water table levels in the Crowdy peat soil than in the peaty gley Wilcocks soil.

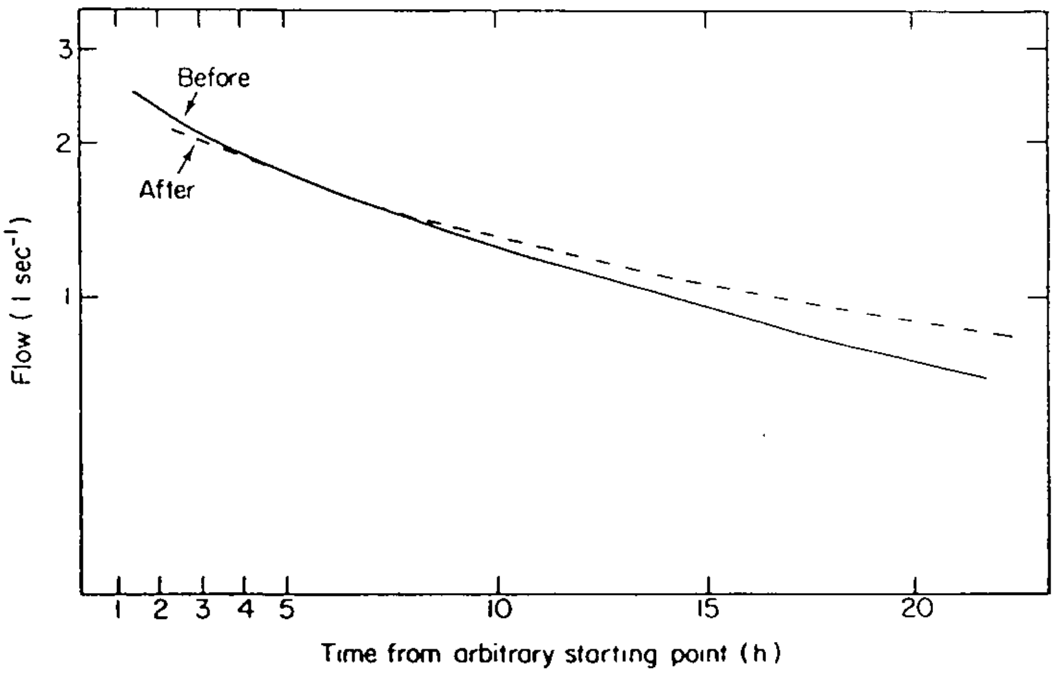



*Figure 4.15 Master recession curves for Staylittle, before and after drainage*

### 4.2.6 Blacklaw Moss

The study period comprised a calibration period, 1959-61, before drainage, and a post-drainage period, 1963-64. The rainfall and runoff parameters for the largest events before and after drainage are summarised in Table 4.5.

*Table 4.5 Comparison of storm runoff events at Blacklaw Moss*

| | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| Before | 0.58 | 20.4 | 3.7 | 46 | : | 6.0 | .07 | 10 |
| After | 1.74 | 20.8 | 4.0 | 58 | : | 2.0 | .18 | 23 |

There was little difference between the two periods in the characteristics of the storms, but there was a large increase in the observed peak flows. Whilst this was partly due to an increase in the average storm runoff coefficient, the main change was to the timing of the storm runoff (Nicholson *et al.*, 1989). The unit hydrograph peak flows were much higher and the response times were much shorter (Fig 4.16).

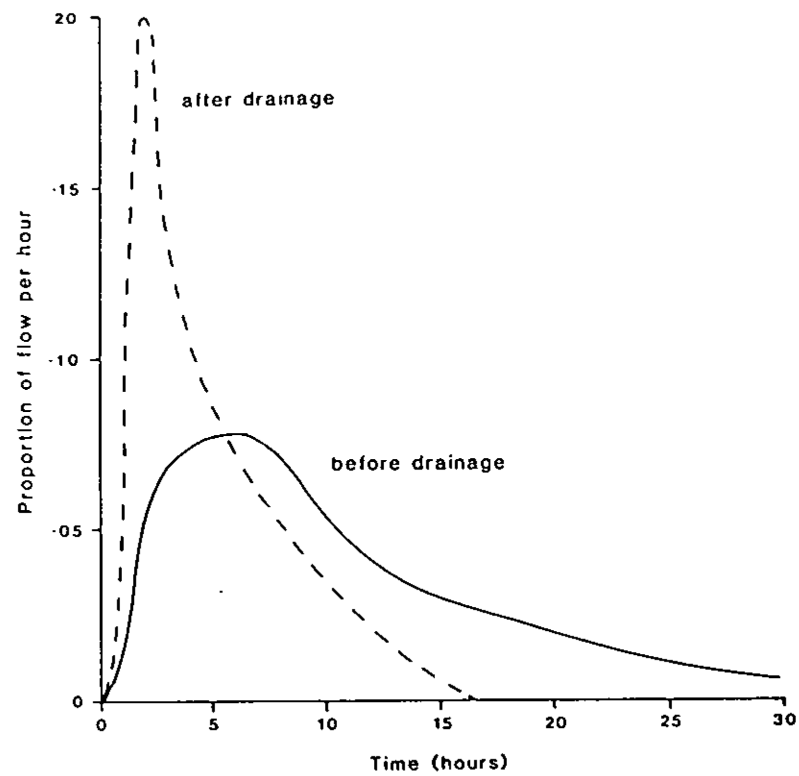



*Figure 4.16 Comparison of one-hour average unit hydrographs for Blacklaw Moss, before and after drainage*

The falling limbs of the hydrographs were analysed to derive master depletion curves, and it was found that there was a much less rapid decline after the drainage of the catchment .(Fig 4.17).

Soil water levels in the two periods are compared in Figure 4.18, based on readings taken from the charts every 2 hours. Prior to cutting the drainage ditches there was a distinctly bi-modal frequency distribution, with peaks at about 10 cm and 30 cm depths, which reflect the most frequent levels in winter and summer respectively. A similar seasonal pattern was noted by Baden and Egglesmann (1964) at a raised bog in northern Germany. After drainage, the water levels were lower, although the two peaks were still evident; their depths may be related to differences in peat stratigraphy. The drainage effect on the soil water was clearly limited, since the water table was still within only 20-25 cm of the ground surface for half the observations. Bearing in mind the high water retention of the peat, and capillary rise above the water table, the soil remained wet for long periods, even after drainage.

The rapid flow response from the drained peat may be interpreted as the result of the large increase in the channel network, (speeding up flows by shortening the slower flow paths through the soil to the channels) and with very little compensating increase in the available storage capacity of the soil (giving limited additional attenuation).

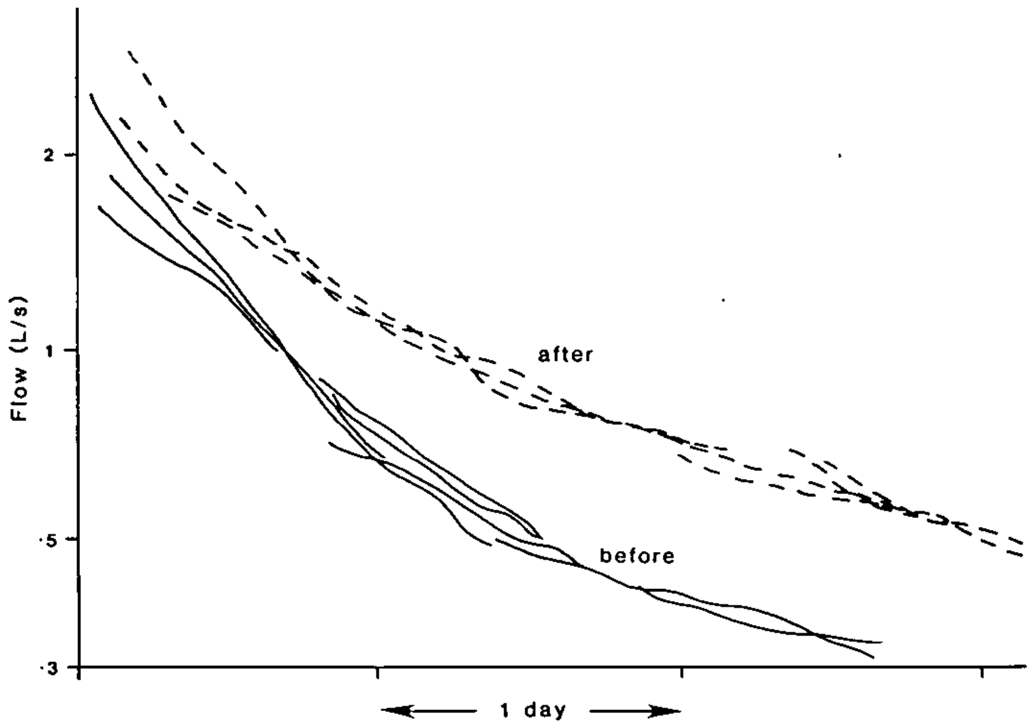



*Figure 4.17 Master recession curves for Blacklaw Moss, before and after drainage*

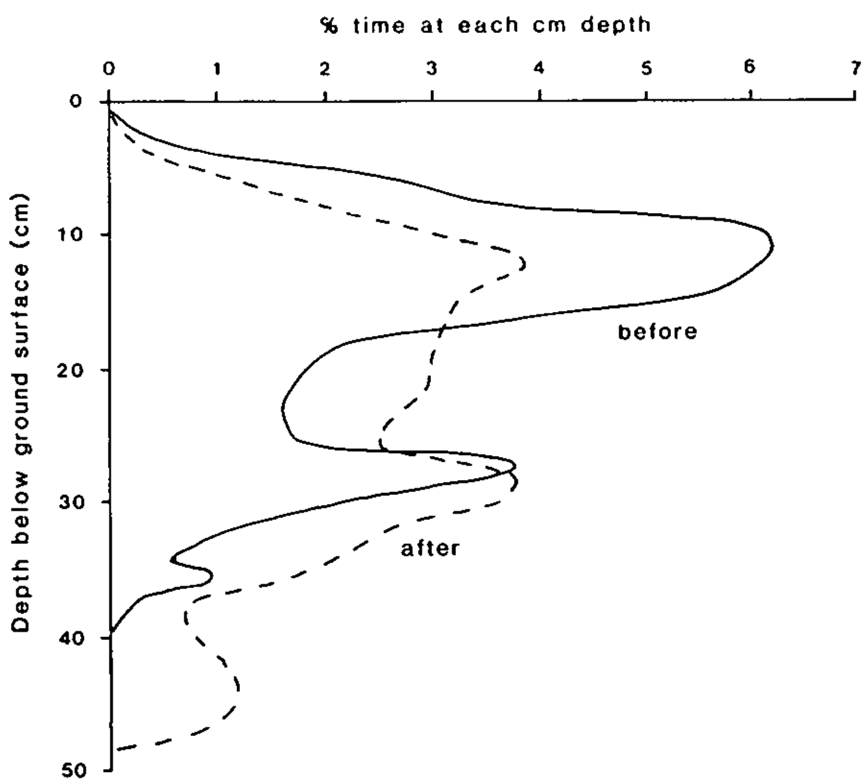



*Figure 4.18 Comparison of water table position before and after drainage at Blacklaw Moss*

## 4.3 COMPARISONS OF EXPERIMENTAL PLOT FINDINGS

The findings of the various plot studies are now compared, in terms of the effect of field drainage on storm runoff peaks, volumes, soil water conditions and dry weather flows.

### 4.3.1 Storm runoff timing

The results from the study sites showed there was an increase in peak storm flows at Withernwick and Blacklaw Moss, but a reduction at the other sites.

The increase was due to a change to a more 'peaky' unit hydrograph (shorter time to peak and higher peak ordinate) and an increase in the average storm runoff coefficient. At the other sites the unit hydrograph from drained land was more attenuated and the storm runoff coefficient was somewhat lower. The changes in unit hydrograph parameters are summarised in Table 4.6 for five of the sites (as discussed earlier the Ballinamore data were not suitable for unit hydrograph analysis).

*Table 4.6 Comparison of one-hour average unit hydrographs, for drained and undrained land, described by the time to peak (Tp) in hours, and the peak hourly flow (Qp) as a proportion of the total storm flow*

| Site | Undrained | | Drained | |
|---|---|---|---|---|
| | Tp | Qp | Tp | Qp |
| Tylwch | 2.0 | .32 | 2.5* | .13* |
| Staylittle | 2.0 | .23 | 2.5 | .14* |
| Withernwick | 5.0 | .09 | 4.0 | .18* |
| Grendon (winter) | 3.0 | .13 | 3.5 | .11 |
| (summer) | 2.0 | .23 | 2.0 | .31* |
| Blacklaw Moss | 6.0 | .07 | 2.0* | .18* |
| Summary parameters (excluding Grendon summer events) | | | | |
| Mean | 3.6 | .168 | 2.9 | .148 |
| Standard dev. | 1.8 | .105 | 0.8 | .031 |
| Coeff. var. | 50% | 62% | 28% | 21% |

* significantly different to undrained land at .05 level.

Due to the effect of shrink-swell on the timing and volumes of flows from clay soils only winter period events (the main period of flood risk) are discussed below.

Table 4.6 shows that the less responsive permeable loam soil outflows became more peaky after drainage, whilst the clayey soils, which give a flashy storm response in their undrained state, became less responsive. This finding is in fact contrary to the change expected from the earlier expressed theoretical views (Trafford, 1973a; Thomasson, 1975; Bailey and Bree, 1981).

Figure 4.19 shows the average unit hydrograph peak ordinates before and after drainage, and indicates that drainage resulted in a more uniform behaviour between sites. The greater uniformity of storm discharge response from drained than undrained land is perhaps not surprising when it is considered that the purpose of the artificial drainage is to impose a required level of water table control. The difference in the effect of drainage between sites may explain the long-standing controversy regarding its implications for arterial flows. Drainage may increase peak flows at some sites and reduce them at others.

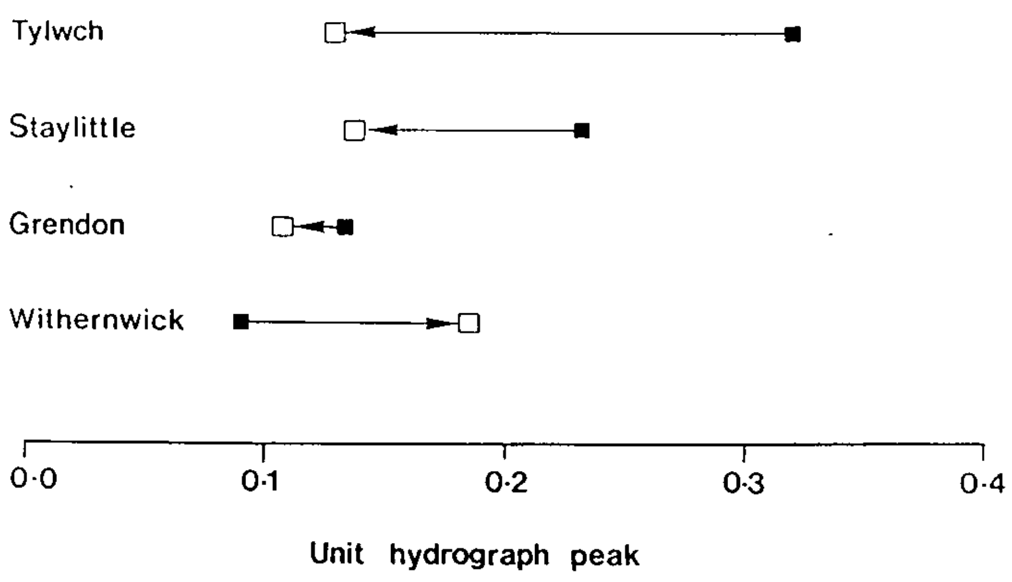



***Figure 4.19*** ***Change in the peak ordinate of the one-hour average unit hydrograph for the experimental plots following artificial drainage***

The drainage of peat sites is considered further in relation to the somewhat similar case of site preparation for forestry (Section 4.5). This is due to the great differences between the properties of peat and mineral soils, and to the different agricultural drainage practices adopted - the peat soils were used for rough grazing and had widely spaced drainage (pipes or ditches) at about 10 m spacings, whilst the four mineral soil sites had a more intensive drainage treatment with moling or subsoiling at 1-2 m spacings, reflecting the greater economic productivity of the land.

### 4.3.2 Storm runoff volumes

The data regarding the effect of drainage on storm runoff volumes are difficult to interpret with confidence. This is due to several factors:

a) Large variations between the runoff coefficients of storms on a catchment, with the same drainage status, even a short time apart;

b) Difficulties in defining the baseflow separation in order to define the net storm runoff due to differences in the time distribution ('shape') of the observed hydrographs and the rate of decline of the falling limb;

c) Site specific factors - the halving of the average storm runoff coefficient at Tylwch after drainage is likely to have been strongly influenced by the coincidence of the severe 1976 drought.

Overall there is little evidence of a consistent change in storm runoff coefficients. There was a clear increase at Blacklaw, and although at Withernwick the average storm coefficent was unchanged after drainage, that at the 'control' site was halved over the same period. At Grendon and Ballinamore, however, the winter storm runoff was slightly greater from the undrained plot; and at Tylwch the coefficients were much lower after drainage, but probably heavily influenced by the drought. At Staylittle there was no apparent change. None of the changes (except for Tylwch) were statistically significant. Other studies (e.g. Armstrong, 1983) have also concluded that whilst field drainage affected runoff pathways it did not alter runoff volumes.

### 4.3.3 Soil water conditions

Measurements of the soil water conditions in the undrained land indicated that at Withernwick the water table was at least 30-40 cm below the ground surface whilst Ballinamore, Grendon and Tylwch had surface or near surface saturation for long periods each winter. Thus the effect of drainage appears to be largely dependent upon the pre-drainage state of the land.

### 4.3.4 Dry weather flows

Except for the equivocal cases of Ballinamore (interflow unmeasured below about 10 cm) and Tylwch (dry weather) the effect of drainage on the low flows from the sites appeared to be consistent, i.e. an increase. This uniformity between sites is in contrast to the differences noted in the effect of drainage on high flows, and it could not be attributed to any short-term dewatering of the soils.

## 4.4 COMPARISONS WITH OTHER FIELD DRAINAGE STUDIES

The central aim of this investigation is to discover some test or set of criteria which can be obtained from an examination of a given site, and enable a tolerably confident prediction to be made regarding whether drainage would improve or worsen flooding downstream. Initial examination indicated that the Withernwick catchment differed from the other sites in being flatter and having a loamy soil whilst the others had more clayey soils. Since the effect of drainage on peak flows might vary between sites due to differences in a number of factors including size, slope, rainfall, soils and geology it is important to have data from many catchments, and to consider as wide a range of variables as possible. A search of the literature indicated four other sites in the British Isles where flows had been measured from drained and undrained land. These are also shown in Figure 3.1 and comprised three sites where drainage reduced peak storm flows at (7) Hayes Oak (Arrowsmith, 1983), (8) Brimstone (Harris *et al.,* 1984) and (9) N Wyke (Armstrong, 1986), together with one site at (10) Cockle Park where peak flows were increased (Armstrong, 1983). All four sites were operated by the UK's Ministry of Agriculture as part of its agricultural studies, but no explanation has been given for their conflicting results regarding peak outflows.

a) Hayes Oak

This site at Purton, near Swindon in Wiltshire was operated by the MAFF as part of a grassland drainage investigation (Parker, 1983). The soil is a heavy clay of the Lawford soil series. Flows were measured from drained and undrained land. Mole drainage reduced peak flows, although storm runoff volumes were similar (Arrowsmith, 1983). Drainage controlled winter water tables at about 40-50 cm depth compared with a depth of only a few centimetres on the undrained control plot.

b) Brimstone

This site near Faringdon in Oxfordshire, was instrumented in a major investigation to investigate the effect of drainage and of different cultivation practices (minimum tillage and conventional ploughing) on flows and water quality (Cannell *et al.,* 1984). The site has a heavy clay soil of the Denchworth soil series and the whole area had shallow subsoiling at 30 cm along the contour to remove an existing plough pan. This was done in dry weather and excavations found no evidence that a channel had been formed (G. Harris, pers. comm.). The drained plots subsequently had mole drains at 60 cm depth and 2 m spacings. Drainage resulted in a lowering of the water table of about 20 cm and peak flows were reduced (Harris *et al.,* 1984).

c) N Wyke

This site near Okehampton in Devon was instrumented to evaluate the economic returns from the drainage of permanent grassland (Wilkins, 1982; Armstrong, 1986). The site has a pelo-stagnogley soil of the Tedburn soil series. This soil has a poorly draining surface layer resulting in surface wetness, underlain at depth by a fractured shale layer which may carry water under pressure (Findlay *et al.,* 1984). The correct drainage design for such soils has consequently been a matter of debate, local tradition uses deep drains to remove water from the shale, but does little to alleviate the surface wetness (Trafford, 1977). The drained plots had mole drains at 50 cm depth and approximately 2 m spacing (Armstrong *et al.*, 1984). Pipe drains were at 85 cm depth. Drainage resulted in lower peak flows (Wilkins, 1982; Armstrong, 1986).

d) Cockle Park

The site near Morpeth, in Northumberland, was established to compare the effectiveness of mole drainage with the traditional local design of closely spaced pipes. The site has a clay loam soil which has variously been described as belonging to the Dunkeswick soil series (Armstrong, 1983) or the Hallsworth series (Armstrong and Davies, 1984) due to a reclassification of the series by the SSLRC. It has subsequently, however, been identified as actually belonging to the Brickfield series (Hollis, pers. comm.). This series is less clayey than either the Dunkeswick or Hallsworth soils. At the Cockle Park site the soil was found to have a cultivation pan at about 25 cm depth, and this was broken up by shallow subsoiling across the slope at 30 cm depth both the drained and undrained plots (Armstrong, 1980). This was intended to remove the effect of the artificially created impeding layer without affecting the 'undrained' status of the control plot. At this site drainage increased peak flows (Armstrong, 1980; 1983).

The results from these independent studies were added to those already analysed in this investigation to provide a database of eight drainage experiments on mineral soils, two of which showed drainage had increased peak flows and six where it had reduced them. Fourteen characteristics were measured for each catchment (Table 4.7), comprising topographic variables (area, slope and altitude), precipitation (annual rainfall and 2-day rain of 5-year return interval), artificial drainage (depth and spacing), soil water regime (winter undrained water table depth and annual wetness class) and soil properties (% clay, depth to slowly permeable layer, depth to gleying and the shallower of the gleyed or impermeable layers, and the integrated air capacity).

The sites ranged in average altitude from 12 m to 295 m and in annual precipitation from 650 to 1300 mm. They had similar artificial drainage with secondary treatment of moling or subsoiling at 1-2 m spacing and 45-60 cm depth. The 2-day 5-year rainfall depth was used to characterise the storm depth-frequency relation for each site using long-term records of daily falls. The choice of a 2-day rather than 1-day duration was to circumvent the problem that many storms span the division between 'rain days' (Ward and Robinson, 1990). The winter water table depth was based on site measurements using tensiometers and dip wells. A slowly permeable soil layer is one which will restrict the downward infiltration of water and is defined here as having less than 7.5% volume of air-filled pores at 5 kPa suction (Fig 3.3). A gleyed soil horizon is indicative of prolonged waterlogged conditions, which results in a distinctive colouration. The percentage clay was used to represent the effect of soil texture which is known to have a strong influence on soil water properties including hydraulic conductivity, water storage and retention. There were insufficient onsite data for two variables : wetness class assessments were obtained from the SSEW regional bulletins, and values of integrated air capacity were obtained from the SSLRC database (SSEW, 1986).

*Table 4.7 Summary characteristics of the experimental plots, distinguishing sites where drainage reduced peak flows and those where it increased them*

| | | | REDUCTION | | | | | INCREASE | |
|---|---|---|---|---|---|---|---|---|---|
| SITE | (1) | (2) | (3) | (7) | (8) | (9) | : | (4) | (10) |
| TOPOGRAPHY | | | | | | | | | |
| Area (ha) | .005 | .25 | 1.7 | 1.8 | .19 | 1.0 | : | 13.5 | .25 |
| Slope (%) | 17.6 | .5 | 2.6 | 1.5 | 3.2 | 7.0 | : | 0.2 | 2.5 |
| Altitude (m) | 100 | 70 | 295 | 82 | 100 | 150 | : | 12 | 85 |
| PRECIPITATION | | | | | | | | | |
| Annual (mm) | 1100 | 650 | 1300 | 700 | 680 | 1060 | : | 650 | 720 |
| 2-day-5yr (mm) | 75 | 48 | 73 | 49 | 48 | 60 | : | 48 | 57 |
| ARTIFICIAL DRAINAGE | | | | | | | | | |
| Space (m) | 1.1 | 2. | 1.3 | 2. | 2. | 2. | : | 1.5 | 2. |
| Depth (cm) | 45 | 45 | 45 | 55 | 60 | 50 | : | 50 | 55 |
| SOIL WATER REGIME | | | | | | | | | |
| Wetness class | V | III-IV | IV-V | IV | IV | IV-V | : | III-IV | IV-V |
| * W.T. (cm) | 0 | 0 | 0 | 0 | 0 | 0 | : | 30-40 | 30-40 |
| SOIL PROPERTIES | | | | | | | | | |
| * Clay (%) | 38 | 52 | 31 | 45 | 49 | 35 | : | 22 | 23 |
| * Imperm (cm) | 24 | 24 | 37 | 25 | 27 | 20 | : | 45 | 40 |
| Gley (cm) | 20 | 60 | 25 | 25 | 25 | 20 | : | 50 | 25 |
| Shallower | 20 | 24 | 25 | 25 | 25 | 20 | : | 45 | 25 |
| IAC (cm) | 4.7 | 5.9 | 6.9 | 5.5 | 5.1 | 5.5 | : | 8.3 | 6.2 |

The sites numbers are (1) Ballinamore, (2) Grendon, (3) Tylwch, (4) Withernwick, (7) Hayes Oak, (8) Brimstone, (9) N Wyke, (10) Cockle Park. See Fig 3.1 for locations
A '*' indicates that the characteristic was statistically different between the two groups of sites (at the .05 significance level)

The Mann Whitney rank test was used to identify statistically significant differences in catchment attributes between those sites where drainage increased peak flows and those where it decreased them. There were no significant differences in terms of the topography, climate or artificial drainage, but statistically significant differences (at .05 level) in three 'soil' parameters. Sites where drainage increased peak flows had deeper winter water tables prior to drainage (depths of 30-40 cm compared with zero at the other sites), deeper limiting permeability horizons (averaging 40 cm compared with 25 cm) and a lower clay content in the surface soil horizons (22% compared with 42%).

The results of these studies indicate a broad distinction between the effect of underdrainage on different types of predominantly mineral soils (Robinson, 1989a,b). Those soils with the poorest natural drainage are generally those with high clay contents. They have long periods of surface saturation through the winter and significant amounts of storm runoff appeared to be generated as overland flow and as near surface flow in the more permeable thin upper layer of the soil. When drained, these soils have a greater soil water storage capacity, and surface saturation was largely eliminated, and rapid topsoil flow greatly reduced. Observed storm outflow peaks were lower from drained than similar but undrained land in winter, the main period of flood risk. In contrast, the sites with more permeable loamy soils do not have such frequent saturation prior to artificial drainage, and most storm runoff appears to be by slower subsurface flow. In such situations, drainage pipes can provide rapid flow routes, and peak outflows were increased.

Values of the two statistically significant soil parameters, the percentage clay and the depth to a slowly permeable layer, are shown in Figure 4.20. There is a broad relation between the two, with increasing clay contents for shallower depths to a limiting permeability horizon. Such a relation may not always pertain, however, due to differences in parent material or to clay illuviation down the profile.

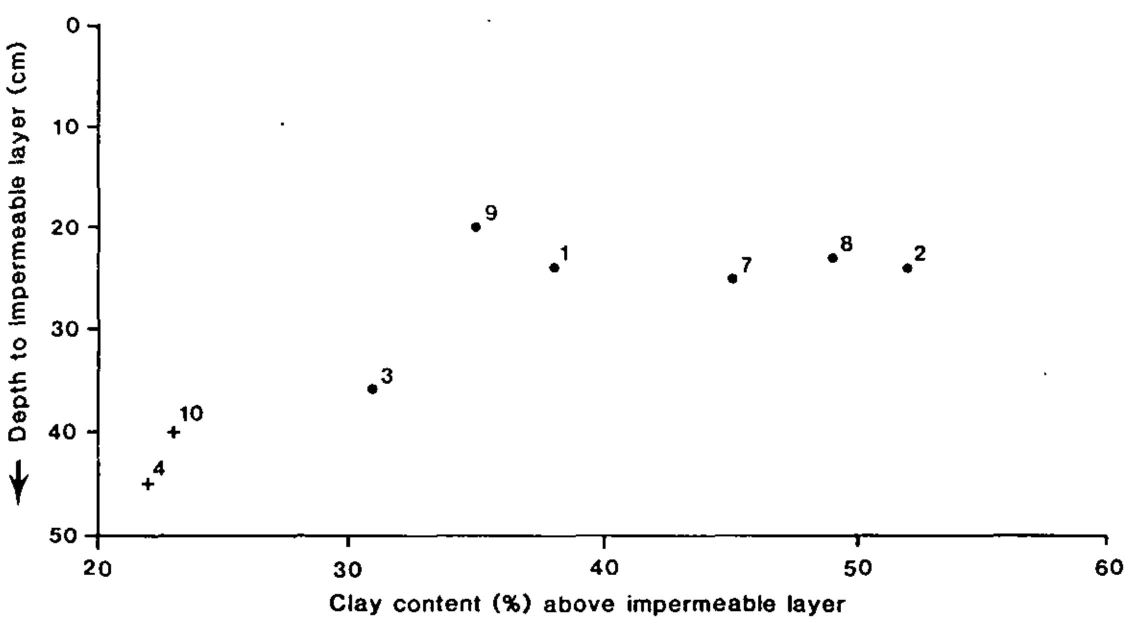



*Figure 4.20 Depth to a slowly permeable horizon and the clay content of overlying layers, at sites where drainage increased storm discharge peaks (+) and reduced them (•)*

The findings of this investigation indicate that the hydrological changes due to drainage may be largely determined by the pre-drainage conditions of the land. Thus it may be possible to suggest the likely effect of a drainage scheme upon peak flows, before the land is drained, by studying the hydrology of the land (especially the soil water regime) and the properties of the soil, including the clay content and the pore space. The most important easily measured site characteristic is the clay content of the soil profile above the limiting horizon (Fig 4.21).

This suggests that it may be possible to predict the effect of drainage on the runoff from a given site. Depending upon the amount of information available this could be achieved in a number of ways. In decreasing order of data requirements (and reliability) these are :

a) Extended field measurements over a number of years to characterise the soil water regime;

b) Single site visit to examine the soil profile and study the properties of the component horizons;

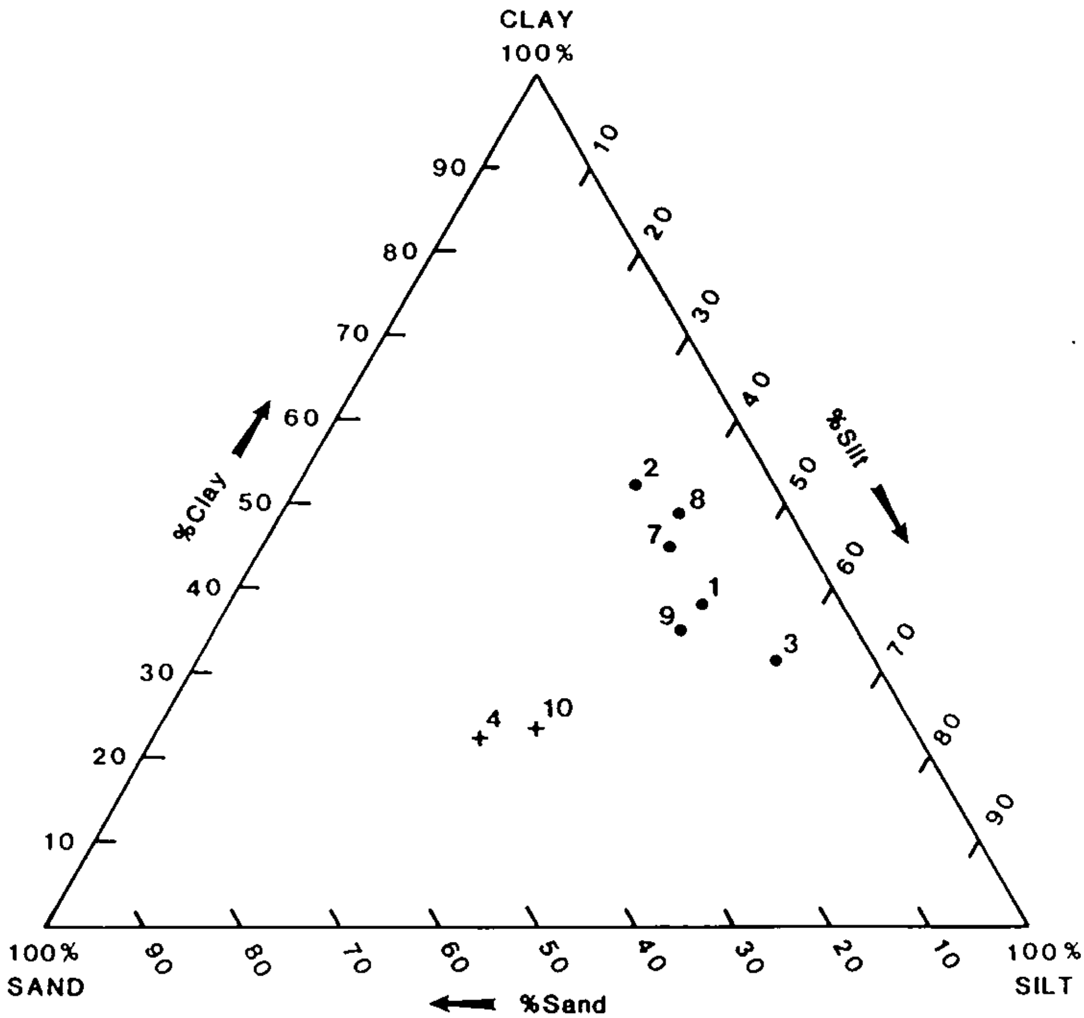



*Figure 4.21 Texture of the soil layers above the limiting permeability horizons for plots where drainage increased peaks (+) and reduced them (●)*

c) Desk study using soil maps to identify the likely soil series and use the properties of other soil profiles belonging to this series. This is the least reliable method, since apart from possible wrong identification of the on-site soil type, there are variations in properties within profiles belonging to the same soil series. Furthermore, land management practices may change some of the soil physical properties; at Cockle Park, for example, overstocking of the land during wet weather resulted in 'poaching' of the surface layers of the soil (Armstrong, 1983).

A search was made of the literature for suitable case histories to test this approach. Warmerdam (1982) reported a reduction in peak flows following drainage of the Hupsel catchment in the E Netherlands. The soils were described as loamy sand, but on further enquiry it was found that the subareas of the catchment which were drained had predominantly clay soils (Warmerdam, pers. comm.). A reduction in peak flows for such soils conforms to the 'pattern' described above.

Comparisons of flow from networks of drains at different spacings may also provide evidence of the effect of artificial drainage on site hydrology if it is assumed that the widest spacing represents conditions nearest to the undrained state. Schuch (1978) described higher peak flows from closer spaced drains at Ellingen, near Munich. This site has a silty clay loam soil (32 cm deep topsoil with 30% clay content) and an average annual rainfall of about 660 mm.

Perhaps not suprisingly, no suitable field data could be found for the effect of drainage of a very permeable sandy soil. Nevertheless it would be instructive to see what the effect of such an extreme case would be, given the apparent increase in flows from loamy soils. Indirect evidence may be obtained from laboratory experiments. Vassos (1982) applied simulated rainfall to an artificial 'catchment' comprising a basin 2.4 m x 1 m in area filled to a depth of 0.1m with sand. Rain was applied at a constant rate and the outflow from this basin was measured. Drainage was represented by different numbers of perforated PVC pipes at an unspecified depth. It was found that peak outflows increased as the number of pipes was increased. This finding conflicts with the theoretical arguments of Trafford (1973) and others described in Chapter 1, and instead adds support to the conclusion of the field sites described above, namely that drainage appears to increase peak flow rates from permeable soils.

In this discussion it must be recognised that other factors than the criteria already identified may also be important at a given locality. Thus under a higher annual rainfall regime the more permeable soils on the textural diagram (Fig 4.21) would become prone to greater waterlogging in their undrained state. They might then respond to drainage in a manner more similar to the clay soils, with a reduction rather than an increase in peak flows following artificial drainage. Another factor, not fully explored in the dataset, is the effect of ground slope. This may tend to reduce the incidence of surface waterlogging, through greater throughflow. There was, however, no difference in the direction of drainage effect at Grendon and Ballinamore, despite the great contrast in ground slope (0.5% and 17.6% respectively).

Storm runoff may also be affected by very site-specific aspects of land management including tillage and soil compaction which have different influences to those of the drainage systems (see Chapter 8). Another factor is the flow capacity of the drainage system, both the field drainage pipes (see Chapters 2 and 5) and the outfall channels (Chapter 6). It seems unlikely, however, that the conclusions from these studies would be significantly affected by surcharging, for two reasons. Firstly, the range of storm magnitudes studied in these generally short-term field investigations are not believed to have exceeded the capacity of the drainage systems. Exact details of the carrying capacity of the field drains are generally not available, and so were assumed to conform to the contemporary design standards (e.g. Smith and Trafford, 1976). Secondly, at the MAFF sites the field drains were deliberately over-designed to prevent surcharging (G. Harris, pers. comm), and their results conform with the findings of this study regarding the impact of drainage on peak flows from different soils.

It was found that drainage resulted in an increase in dry weather baseflows at the sites analysed in this Chapter (Section 4.2). The MAFF sites did not, unfortunately, provide suitable data to study the impact of drainage on low flows since they had only shallow flow collectors at the control sites. In contrast, with the exception of Ballinamore and Grendon, the study sites described in this investigation recorded total (undrained) flows into field ditch systems that were of a similar depth to the drainage systems. Valid comparisons between baseflows under drained and undrained land conditions could therefore be made.

## 4.5 SPECIAL CASE OF PEAT SOILS

Peat forms where the rate of formation of plant tissue exceeds the rate of decomposition. This usually occurs where conditions are unsuitable for the activity of soil microorganisms causing this breakdown, and a principal factor is waterlogging. The two sites with peat soils showed very different effects of drainage on peak outflows. At Staylittle pipe drainage of the amorphous Crowdy series peat led to a reduction in peak flows. At Blacklaw Moss the open ditching of the fibrous Winter Hill series peat increased the peak discharges. Since the two sites differed in terms of their rainfall, slope and drain types, in addition to their peat type, it was not possible to reach definite conclusions regarding the importance of these factors.

Other peat drainage studies have also found conflicting results, with increases in peak flows at some sites and reductions at others. An increase in peak flows was also noted following the drainage of peat soils at Blacklaw Moss (6), Coalburn (Robinson, 1986b) and Chiemsee in S Germany (Schuch, 1976), but other studies near Bremen in N Germany (Baden and Eggelsmann, 1964), Glenamoy in W Ireland (Burke, 1975) and Staylittle (5) showed a reduction in peak flows after drainage. Peat samples were taken from Blacklaw, Coalburn and Glenamoy for analysis, and it was found that there was little difference between the sites in either the peat constituents (predominantly *Sphagnum* and *Eriophorum*) or in the degree of decomposition (R.A. Robertson, pers. comm.). Further work is needed to clarify the downstream effects of peatland drainage.

In contrast to the conflicting results for peak flows, there is almost complete agreement of experimental findings that peat drainage augments low flows in dry weather periods. The mechanism for this is not yet clear, and may involve partly a small, but general, gravity drainage of water from the peat profile near to the drains, and partly the tapping of shallow, localised mineral material aquifers.

## 4.6 SUMMARY AND CONCLUSIONS

Data from six field drainage experiments were examined. Standard analysis techniques were used, although for storm runoff timing studies the NERC (1975) method was modified to provide an improved estimate of the average unit hydrograph. In the data set studied the effect of drainage on peak rates of outflows appears to be strongly related to the soil water status (and hence soil type) of the undrained land. The degree of waterlogging at a site will depend upon a number of factors, of which the most general are the incoming rainfall and the depth and clay content of the topsoil.

Field drainage was found to increase peak flows, not from mole drained clay soils as has generally been thought (Trafford, 1973a; Thomasson, 1975; Bailey and Bree, 1981), but from the more permeable loamy soils. These soils already have a significant amount of available soil water storage and discharges are predominantly by subsurface, rather than surface and near surface routes. The effect of artificial drainage is to promote more rapid subsurface flow. 'I think the limited evidence would support your contention that on permeable lowland soils field drainage would increase flood risk' (J. Rands, MAFF pers. comm.).

In contrast, on clay soils (and on more permeable soils in high rainfall areas), the soils are waterlogged for long periods and there is little available soil water storage. Storm period flows are predominantly on and in the surface few centimetres of the soil. Artificial drainage largely eliminates such surface runoff and reduces peak flows.

Whilst the analysis and comparison of many studies described here provides a considerable advance on individual single-site studies, it must be emphasised, that for a given site of interest there may be other factors, not represented in this data set, which may be important. The mineral soil sites all had a similar type of artificial drainage (depth and spacing), and different results might have been found where, for example, secondary treatment had not been used and the effective drain spacing was consequently much greater. The type of crop, depth of ploughing and compaction of the topsoil by heavy machinery or farm animals may also affect the flows from farm land. The drainage sites discussed above, both those analysed in detail and those based on published accounts, cover a wide range of drainage situations, but it is inevitable with a finite number of empirical studies that they cannot cover the complete range of conditions encountered in artificial drainage (over 100,000 drainage schemes were carried out in England and Wales alone in the 1970s). There is a need to generalise from the limited number of field experiments to study the sensitivity of drainage effects on runoff under different site characteristics. This is investigated through the use of a mathematical model described in Chapter 5.

# 5. Modelling flows from drained and undrained land

## 5.1 INTRODUCTION

The preceding chapter presented the findings of a number of field studies, which, although covering a wide range of climate, slope, soil types etc., could only represent a fraction of all possible combinations of site attributes. In addition, some factors such as drain spacing did not differ greatly between the different plot studies, and so their effects were not discernable. Consequently there is a need to generalise the findings of these plot studies, both to support the results obtained at the individual study sites and also to investigate the effect of drainage under different conditions. The means chosen to achieve this in the present study was to use a mathematical model to simulate flows from drained and undrained lands.

If the model could be validated using data from the study sites, and found to produce satisfactory simulations, then it may be applied to other conditions where flow data are not available. It could, for example, be used : a) to extrapolate from observed conditions to those not included in the observed data, such as very large storm events (taking care to be aware that system thresholds may have been crossed); b) to simulate flows at ungauged sites; c) to explore the sensitivity of flow changes to different values of site characteristics. In selecting a model a number of criteria were used; the model should be :

a) capable of producing hourly flows, so that flow peaks may be studied;

b) capable of dealing with long time series of input weather data in order to cover a wide range of storm events to show the effect of drainage under different conditions of ground wetness and storm magnitude;

c) able to deal explicitly with drain spacing and depth, so that the effect of different drainage system designs could be explored;

d) able to deal with measurable soil properties, such as porosity and hydraulic conductivity, so that the effect of different soil types could be studied;

e) already developed and well tested, prior to this study.

The model chosen for this purpose is DRAINMOD (Skaggs, 1980), and it is described in the following sections.

## 5.2 DRAINMOD - MODEL DESCRIPTION

This computer model was developed at North Carolina State University for the design and evaluation of drainage and associated water management systems

(Skaggs, 1980; 1986). For a specified drainage system (depth and spacing) the model uses soil physical properties and weather data (rainfall and potential evaporation) to predict hourly outflows (surface and subsurface), water table position and the soil water content in the unsaturated zone. The model is designed to be applied to relatively flat sites with high water tables and an impermeable layer at a known depth below the surface. It has been widely tested in the USA (Skaggs, 1982; Skaggs *et al.*, 1981) and has been adopted by the US Department of Agriculture for use by its agricultural advisors as a tool in optimizing the design of surface and subsurface drainage systems.

The model was designed to be applied to ungauged catchments by using parameters which could be derived in the field. As Skaggs *et al.* (1981) noted, it is possible with many hydrological models to obtain 'a nearly perfect agreement with a given set of observed data by juggling the input parameters to optimise the fit. However, such results would be useless as a test of model reliability. The practical use of the model depends not only on its ability to reliably predict ... but also on the premise that the required inputs can be obtained from ... site characteristics'.

A copy of the program DRAINMOD V3.0 was obtained from Prof R.W. Skaggs at N Carolina State University. It had been written in Fortran for use on an IBM PC. For ease of running with large datasets, comprising long time series of weather data, the program was modified to run on the IBM 4381 mainframe computer at Wallingford. This also considerably reduced the running time which was about 15 minutes per year of simulation on a standard IBM PC with 256K of memory using DOS2.0, or a later version, and 2-3 minutes if the machine has a 8087 math coprocessor (Nolte, 1986). A number of modifications were made to the model in the course of its use, and the more important ones are summarised in Section 5.2.5.

A simplified picture of the model is given in Figure 5.1. The model calculates fluxes for a 2-dimensional section of soil of unit surface area perpendicular to a series of parallel drains (pipes or ditches) spaced at a distance 'L' apart and at 'd' above the impermeable layer. By assuming a consistent shape of the water table between the drains the water balance of the section for a time increment $\Delta t$ may be calculated :

$$\Delta V = Q + ET - F \quad (5.1)$$

where $\Delta V$ is the change in the volume of air-filled pores, Q is the drain flow, ET is the actual evaporation and F is the infiltration of water into the section in time $\Delta t$. Allowance for deep seepage is not currently included in the model.

The amounts of surface ponding and overland flow (if any) are calculated from a water balance at the soil surface :

$$P = F + \Delta S + OF \quad (5.2)$$

where P is the total precipitation (assumed to be liquid rain), F is the infiltration, $\Delta S$ is the change in surface depression storage and OF is the overland flow during the time increment $\Delta t$.

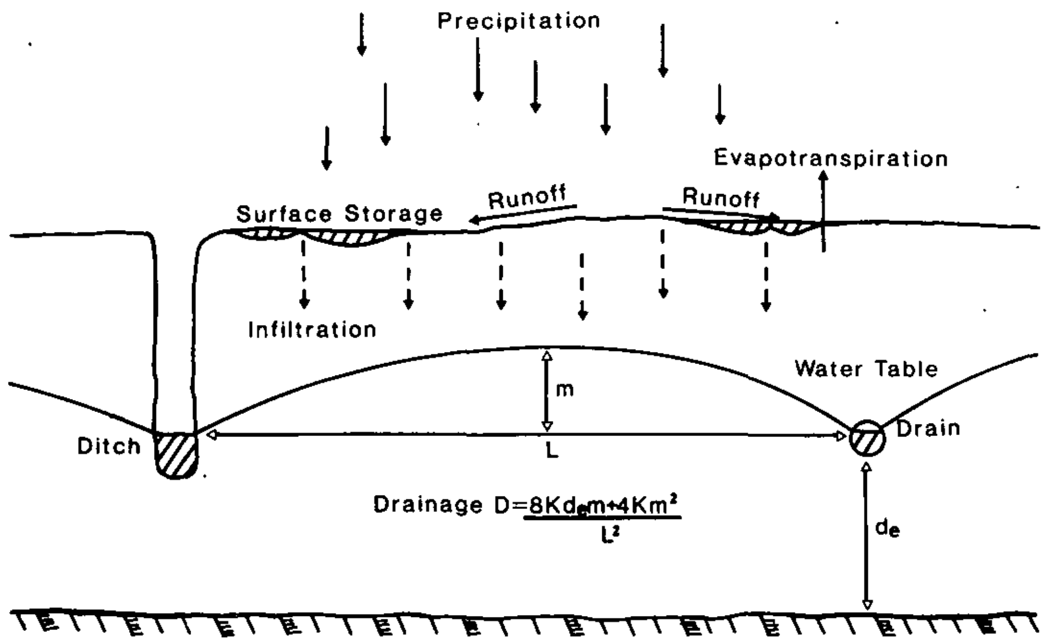



*Figure 5.1 Main components dealt with by DRAINMOD*

The basic time increment used is 1 hour, but this may vary with the prevailing hydrological conditions. Thus, when rainfall intensities exceed the infiltration capacity of the soil a time increment of 0.05 hour (3 minutes) is used. Conversely when there is no rainfall, if the evaporation rates are small and the water table elevation is changing only slowly, a time step of one day is adopted.

The model components are described in the following subsections. Data requirements and the application of the model to field data are detailed in Sections 5.3 and 5.4. Its use to investigate the sensitivity of flow changes to artificial drainage with differences in site parameter values is discussed in Section 5.5.

### 5.2.1 Infiltration

The rate of entry of water into the soil through the soil surface depends upon a number of factors including the soil properties, initial soil water content and the rainfall. For the majority of the time, in humid temperate regions, the ability of the soil to absorb water will be greater than the rate of rainfall, and the infiltration rate will be determined by the rainfall rate reaching the ground (with allowance for interception losses on vegetation). It is only in extreme rainstorms with very high rainfall intensities that the ability of the soil surface to absorb rainfall may be exceeded, resulting in surface ponding of water and overland flow.

Many formulae have been proposed to predict the variation in infiltration capacity, and the method adopted in DRAINMOD uses the equation proposed by Green and Ampt (1911) in a classic study of the flow of air and water through soils. This equation has been found to give good results in a number of studies by other investigators, and has physically based parameters that can be derived experimentally for a given soil.

Starting with the Hagen-Poiseuille equation for flow through capillary tubes, they assumed that the wetting front was a sharply defined surface which separated completely saturated soil above from unaffected soil below (Fig 5.2).

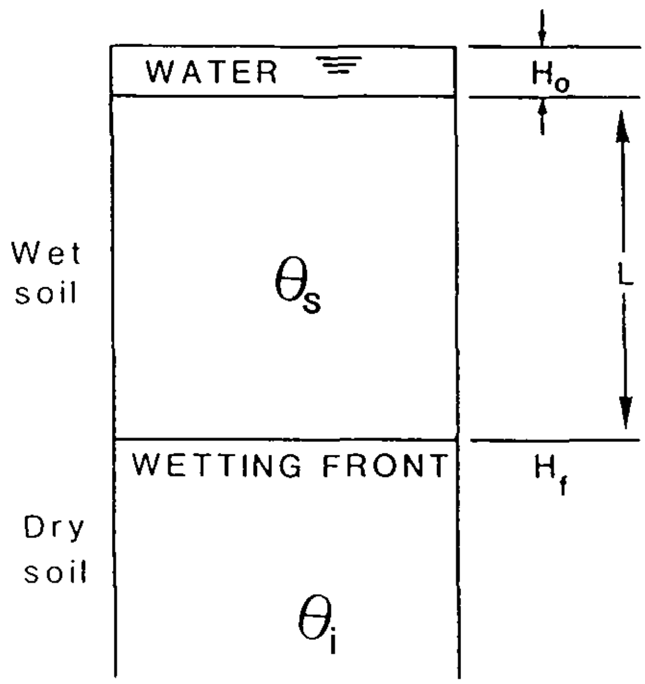



*Figure 5.2 Ponded water infiltration, showing the parameters used in the Green and Ampt equation*

For a soil with water ponded on the ground surface to a depth $H_o$ with the wetting front at depth L and a capillary suction at the front of $H_f$ the rate of infiltration is given from Darcy's law as :

$$f = K (H_o + L + H_f) / L \tag{5.3}$$

where K is the effective hydraulic conductivity above the wetting front (less than for saturated conditions due to air entrapment). Note that $H_f$ is a negative quantity.

The cumulative infiltration, F, may be expressed as the product F = M L, where M is the initial soil water deficit (or fillable porosity) and comprises the difference in volumetric water content between the initial water content and saturation. Assuming that the head of water ponded on the surface, $H_o$, is negligible in comparison to $H_f$ and L yields :

$$f = K + (K\ H_f) / L \qquad (5.4)$$

and substituting L = F / M, yields the Green-Ampt equation :

$$f = K + (K\ M\ H_f) / F \qquad (5.5)$$

For a given soil with a specified initial water content this may be written as :

$$f = A / F + B \qquad (5.6)$$

where A and B are parameters that depend upon the soil properties, initial water content and distribution and surface conditions such as plant cover, crusting etc.

Although originally derived for deep, homogeneous soil profiles with a uniform initial water content, the Green and Ampt equation has been used with good results for profiles that become denser with depth (Childs and Bybordi, 1969) and for soils with partially sealed surfaces (Hillel and Gardner, 1969). It has been satisfactorily applied by a number of authors (Whisler and Bouwer, 1970; Mein and Larson, 1973). The equation assumes that the infiltration capacity is dependent only upon the cumulative infiltration, F. The work of Mein and Larson (1973) compared the results of this equation to the Richards equation for a wide range of soil types and steady application rates and their results imply that for deep, homogeneous soils with a uniform initial moisture content this assumption is valid. This work was subsequently extended by Reeves and Millar (1975) for the case of erratic rainfall with an unsteady rate that was sometimes greater and sometimes less than the infiltration capacity of the soil. They also showed that the infiltration capacity could be approximated as a simple function of the cumulative infiltration, regardless of the previous variations in the application rate. The pattern of decline in the infiltration capacity for different initial ground conditions is shown in Fig 5.3.

Inevitably this equation is a simplified picture of the infiltration processes in field soils. For example, it makes no allowance for 'bypass flow' in dry soils enabling the rapid penetration of water to depth, as observed and recorded at the Ballinamore and Grendon field sites. Such macropore flow is likely to be of most importance for shrinking soils in the late summer/autumn period, especially under intense rainfall for short periods in localised thunderstorms. It will be of less importance for winter storms (the main season of river flooding) when the clay soils swell and cracks close up.

The model assumes that water infiltrating into the soil first replenishes any deficit of water content below 'field capacity' and additional water entering the soil is then added to the saturated zone within the hour. There is no allowance in DRAINMOD for the formation of a perched water table at soil horizon boundaries.

### 5.2.2 Subsurface drain flows

The approach taken in DRAINMOD is to assume that subsurface flows may be divided into vertical unsaturated flow (either downwards to the water table or upwards for evaporation) and horizontal saturated flow.

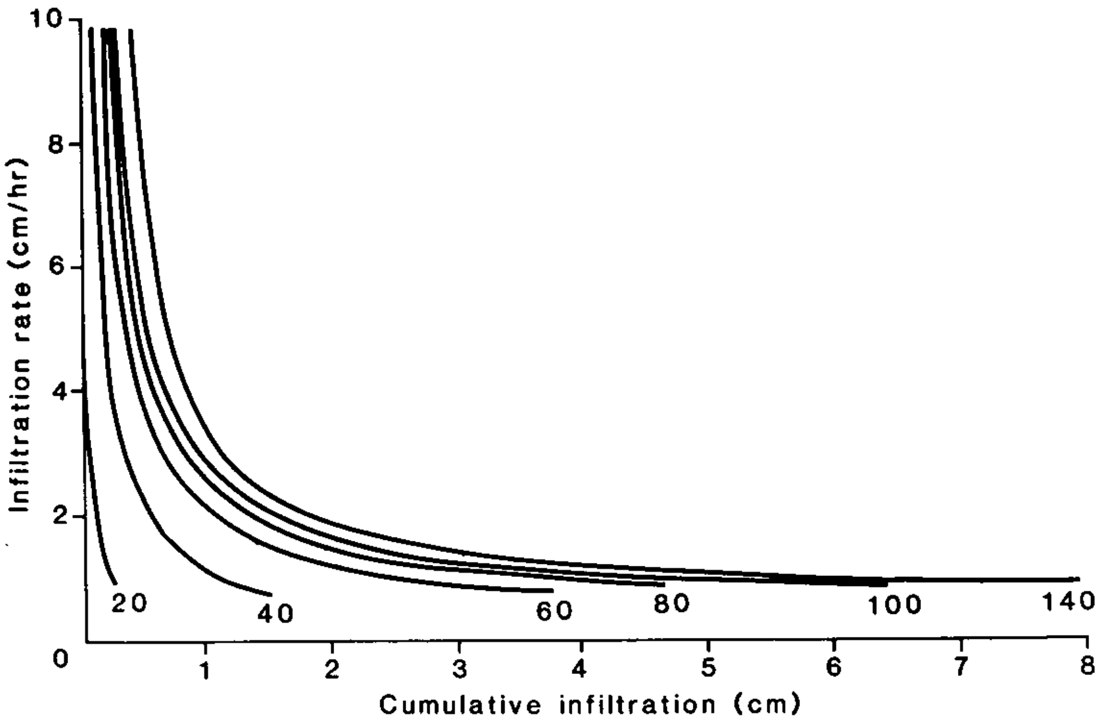



*Figure 5.3 Decline in the infiltration capacity of a sandy loam soil initially drained to equilibrium at various initial water table depths (Skaggs, 1981)*

The Hooghoudt equation is used for the computation of drainflow, q, which is evaluated in terms of the difference in elevation between the water table midway between the drains and the water level in the drains, m, i.e. :

$$q = (8\ K\ d_e\ m + 4\ K\ m^2)\ /\ L^2 \qquad (5.7)$$

where K is the effective horizontal saturated hydraulic conductivity, L is the drain spacing and $d_e$ is defined below. The term $(8\ K\ d_e\ m)\ /\ L^2$ is the flow contribution through the soil between the water level in the drain and the impermeable layer, and $(4\ K\ m^2)\ /\ L^2$ is the flow contribution from the soil above the water level in the drain. The water table between the drains is assumed to be eliptical and to change elevation, but not shape, over time as water is added and removed (Bouwer and van Schilfgaarde, 1963).

The Hooghoudt equation is based on the Dupuit-Forchheimer assumptions that flow in the saturated zone is horizontal and that its velocity along these streamlines is proportional to the slope of the water table. These assumptions may be valid for vertically walled ditches and for flow at some distance away from pipe drains, but the flow paths will be radial in the region near the pipes. This convergence close to the drains will depend upon the spacing between drains and the depth of the soil below the drains. As the flow lines converge on the pipe drain, there is an increase in the flow velocity and, by

Darcy's law, an increased head loss. Accordingly, Hooghoudt derived an equivalent depth, de, which is smaller than the actual depth, d,. of the impermeable layer beneath the drains, and when substituted for d in Equation 5.7 will tend to correct drainage fluxes for this near-drain convergence. The calculation of this parameter is described in Section 5.3.2. The Hooghoudt equation is discussed in numerous papers (e.g. van Beers, 1976; Dieleman and Trafford, 1976; Withers and Vipond, 1974).

The Hooghoudt equation may be used for shallow soils with drain spacings as close as only 1 or 2 metres if the water table gradients between the drains are low, so the flow is predominantly horizontal. The limit of validity for the Dupuit formula is that the gradient of the water table surface is less than 0.2 (Lencastre, 1987), or the square of the gradient is << 1 (Bear and Verruijt, 1987). For a system of drains this means that it is valid if the spacing, L > 1.4 $d_e$ (H. Lumadjeng, pers. comm.). This condition is easily met for the drainage experimental sites as the spacing of the secondary treatments (moling/subsoiling) is about an order of magnitude larger than the effective depths of the restricting barrier. Although soil cracking and bypass flows will not conform to the assumptions of a homogeneous porous medium, the principal period of interest for this study was the effect on peak flows in winter (the time of highest flows for all but the smallest of catchments). At this time the effect of any cracks will be at their most limited.

For the 'undrained' land the drain depth and spacing used for the Hooghoudt equation were represented by the field boundary ditches. In this study this was taken to be an arbitrary 50 m spacing, and the depth was assumed to be the same as that of the mole drains.

For layered soils the effective hydraulic conductivity is calculated as the weighted mean of the different thickness layers below the water table. The Hooghoudt equation is not suitable for soils in which a higher permeability soil underlies one of low permeability, in which case the method of Ernst should be used.

The maximum possible drainflow rate is determined by the hydraulic capacity of the drains. A design capacity or 'drainflow coefficient' equivalent to an average areal discharge of 10-20 mm/day is typically used in drainage system design.

If the water table rises to completely inundate the ground surface then water can move freely to above the vicinity of the drain with most of the water then entering the soil in that region. Under such circumstances the streamlines will be concentrated at the drains and the Dupuit-Forchheimer approximations will not hold. For this case Kirkham (1957) derived the following equation :

$$q = [4 \pi K (H - r_e)] / [G L] \qquad (5.8)$$

where H is the total head of water over the drains (ponded depth, $H_0$, plus the drain depth), L is the drain spacing and G is calculated from the configuration of the drainage system (Kirkham, 1957 Equation III.33). In DRAINMOD the maximum drainflow is limited by the design drainflow coefficient.

The Hooghoudt equation deals with 'steady state flow', i.e. when the flow for a given site is determined by the mean head, m, over the time interval considered. For situations where flows are varying rapidly it may be argued that a 'non-steady flow' solution is required, whereby allowance is made for changes in water table over the time step considered, and this would involve the addition of extra terms to the steady state equation (e.g. Bloemen, 1974). Given the need to simulate long record lengths at short time steps, a steady state solution was adopted for this investigation due to the savings in computer time this permits. The short data interval used (1 hour) would limit the amount of change over the time step, and this data interval was found to be adequate to describe the storm flow response analyses described in Chapter 4.

### 5.2.3 Soil water content and actual evaporation

Actual evaporation is computed in DRAINMOD by considering both the potential evaporation (supplied as data input) and the soil wetness (calculated by the model). The water content in the unsaturated soil above the water table is assumed to conform to a hydrostatic pressure head distribution. That is to say, it is assumed to be the same as a column of soil drained to equilibrium with a static water table; matric suction increasing directly with elevation and equalling the height above the water table. The water content profile above the water table then corresponds to the soil water characteristic. This is obviously a simplification, particularly for low conductivity soils which may take some time to drain to 'field capacity'. Under natural conditions rainfall and evaporation seldom permit soil water contents to reach a state of equilibrium over the whole profile. Nevertheless despite its limitations the field capacity concept is widely used, and this form of equilibrium profile is more realistic than assuming a uniform water content throughout the unsaturated zone.

When the water table is shallow, potential evaporation demands may be met by upward capillary movement of water to the ground surface or plant root zone. This upflux may be estimated as :

$$q_u = K(h) - K(h)\ [dh/dz] \tag{5.9}$$

where z is the height above the water table, and K(h) is the unsaturated hydraulic conductivity (which is a function of the pressure head, h). Numerical solutions to Equation 5.9 can also be obtained for layered soils (with differing K(h) relations).

By solving this equation subject to a large negative suction the maximum upflux for a given water table depth can be estimated. If the upflux is insufficient to supply the evaporative demand then water is removed from the root zone of the soil to a minimum water content $\theta_{LL}$, representing the 'wilting point' (Figure 5.4).

Thus, when the rate of upflux is less than the potential evaporation rate, the actual evaporation will continue at the potential rate for as long as water is available to be extracted from the root zone, but once this is exhausted the evaporation rate will fall to that dictated by the rate of upflux from the water

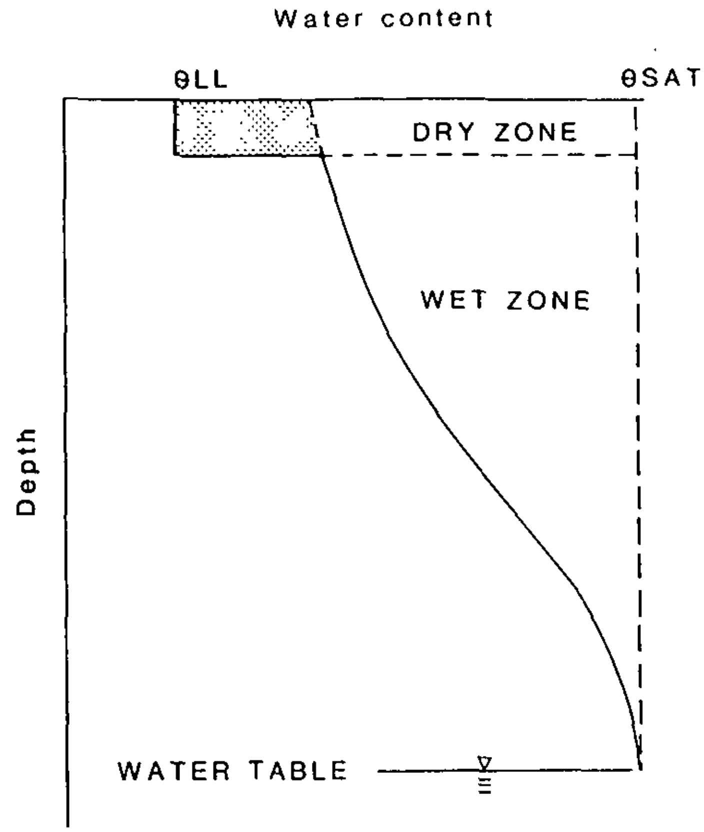



*Figure 5.4* ***Soil water distribution when evaporative demand exceeds the maximum rate of upflux from the water table, resulting in the creation of a dry layer in the root zone***

table. Subsequent rainfall is assumed to first replenish the deficit in this 'dry' zone before any water is allocated to deeper layers. The rooting depth and wilting point suction are model input parameters.

### 5.2.4 Surface ponding and overland flow

Rainfall which fails to infiltrate into the soil must first fill a specified average depth of surface depression storage before general overland flow can occur. Since overland flow is much quicker than subsurface flow velocities, the treatment in DRAINMOD assumes that it reaches the outlet channel within the hourly time step. The water in the depression storage subsequently infiltrates into the soil. The greater the depression storage capacity, the larger will be the duration and amount of infiltration, the greater the the rise in the water table and the smaller the amount of surface runoff. Depression storage capacity may vary seasonally in reality, but it is assumed to be time-invariant in the model. There is also a second surface storage parameter in DRAINMOD which is smaller or equal to the depression storage capacity threshold before general overland flow, and represents the depth of ponded water necessary before water can migrate freely over the surface to enter the soil surface above the nearest drain. It is assumed that both surface storage parameters are constant throughout the year.

### 5.2.5 Modifications made to DRAINMOD

A number of relatively minor modifications were made to the DRAINMOD program. These included changes to make the model easier to use, additional output information on system variables and the correction of some small errors. These should not, however, cause significant departures between the simulation results and those produced using the standard version of the model. Nevertheless, for completeness, they are documented below :

1) The micro computer version of DRAINMOD was modified to be run on a mainframe computer. This was to improve the ease of interfacing the model with the large datasets of weather data, and to reduce the time taken to simulate long time series of data.

2) The program was modified to accept all data inputs in metric units.

3) The calculation of daily potential evaporation using the Thornthwaite approach was replaced by user supplied values that could be obtained using more reliable methods (if suitable meteorological data are available).

4) The supplied version of the model distributed the daily potential evaporation in a very simplistic manner, with a constant rate during the 'daylight' hours (0700 - 1800 inclusive) and zero loss during the 'night' and during rainfall. This was modified to give a more realistic diurnal distribution of evaporative potential, based on values used in the IH lumped conceptual model (C. Eeles, pers. comm.), with proportional hourly losses 0700 - 1800 hours as follows :

   0.020 0.055 0.087 0.108 0.114 0.116 0.119 0.121 0.114 0.087 0.046 0.013

   These values are inevitably an approximation since the daily pattern may vary with plant type (due to differences in stomatal control), amount of intercepted water and season of the year.

5) Certain input parameters which depend upon the drainage system (including the equivalent depth, $d_e$, and Kirkham's G) are now calculated automatically in the program. This slightly simplifies the setting up of the datafiles and, more importantly, ensures that their values are recalculated for any change in the drainage configuration.

6) Greater flexibility in model operation, with the ability to run the model for just part of a data series, rather than having to edit the weather data input file.

7) Changes to output options allowing : a) listing of predicted and observed hourly flows, b) depth duration summaries for the simulated water table levels.

8) Modification to Kirkham ponded water flow : It was found that DRAINMOD sometimes produced very large jumps in hourly flows when the water table reached the surface. This might, perhaps, be expected on a physical basis as the soil water storage capacity is exhausted and overland flow moves much more rapidly to the outlet than drainflow. However, some of these peaks were solely drainflow. On occasions they were greater than the hourly rainfall, with a consequent rapid drop in the water table as the upper soil layers were suddenly 'dewatered'. After detailed study of the model's hourly fluxes it was found that this resulted from the drainflows predicted using the Kirkham equation being much greater than those using the Hooghoudt equation (for similar soil water conditions). When the model switched from using one equation to the other this could result in very great differences in successive hourly flows. This difference was much larger than could reasonably be expected, and to prevent it occurring the maximum hourly drainflow from the Kirkham ponded water equation was limited to the available quantity of ponded water, subsequent flow being generated by the Hooghoudt equation.

9) The model was forced to run at a time step of 1 hour or less, rather than using a daily time step in dry periods. This was intended to provide more accurate low flow simulations.

### 5.2.6 Additional input parameters

The model was designed primarily for water management purposes to determine optimum drainage scheme configurations and contains a number of other parameters that are not of direct concern to this report. These control, for example, the amount of additional irrigation water either by surface application or as subirrigation (maintaining artificially high water levels in the outfall drains to cause water to flow back up the field drains into the soil). Other parameters control output information including the length of time that the upper soil layers are wetter than specified values, since this may influence crop growth or bearing strength for machinery.

## 5.3 INPUT DATA REQUIREMENTS

The model requires three main types of data : weather data (rainfall and potential evaporation), soils data (including water retention and hydraulic conductivity) and drainage system design (including depth and spacing). Examples of the input files are given in Section 5.4. Guidelines on the choice of appropriate values for some of the input parameters are given in Skaggs (1981) and USDA (1985), and the following is a summary of the most relevant aspects for the purpose of this investigation.

### 5.3.1 Weather data

The model uses hourly rainfall depths and daily potential evaporation. These are the shortest time intervals for which such data are generally available. The number of sites with long series of such data is steadily increasing; for example in a nationwide study of extreme hourly rainfall May and Hitch (1989) used data from 234 gauges, compared with 112 available to the Flood Studies Report (NERC, 1975). Potential evaporation estimates may be calculated from meteorological data or, less reliably, from open water pans with a correction coefficient. For this investigation Penman estimates for short grass cover were used. Whatever the method of calculation it may be that these estimates are not available for a particular site, or are perhaps incomplete. In a study of daily soil moisture deficit modelling, Calder *et al.* (1983) showed that whilst good rainfall records were essential over the period of study, an approximation to the annual pattern of potential evaporation was adequate. This was because the latter is much more conservative from year to year, and the distribution of daily values over the course of a year may be estimated from a knowledge of the annual total. They suggested that daily potential evaporation could be approximated by a sine wave of the form :

$$PE = 1.5\ (1 + \sin\ [(360\ i\ /365) - 90]) \qquad (5.10)$$

where the angle is in degrees, i is the day number (counting from Jan 1st) and the leading multiplier is a scaling factor to yield an area under the curve which is equal to the local long-term annual average. This average may be estimated from nearby stations or from maps (e.g. Smith, 1967).

### 5.3.2 Soil properties

These comprise the largest number of individual parameters that have to be estimated for input to DRAINMOD. They are all physically based properties that may be obtained directly by fieldwork at the study area or, less accurately, may be estimated from other, more easily obtained information. In many cases some of these input data will not be available from conventional data sources and since it is not always possible to directly measure them the necessary inputs may have to be approximated. Methods for approximating the data and an indication of the relative accuracy of different approaches are discussed below.

DRAINMOD has previously been applied to a wide variety of soil types, from sandy soils to ones with a high clay content (Table 5.1).

*Green and Ampt infiltration parameters*

To calculate the infiltration capacity rate DRAINMOD requires a table of A and B values for different initial water table depths. For each storm, appropriate values corresponding to the water table position at the start of the rainfall are obtained by interpolation from this table. The parameter values are kept constant during the storm, and will only be changed at the start of a 'new' storm (defined in the model as at least two consecutive hours without rain). As an example, if the initial water table depth at the start of a

*Table 5.1 Summary of soil types already used with DRAINMOD, showing texture, topsoil hydraulic conductivity and depth*

| USDA soil series name and texture | Ksat (cm/hr) | Depth (cm) | Source |
|---|---|---|---|
| Timotly sandy loam | 1.0 | 100 | Skaggs (1982) |
| Lumbee sandy loam | 1.0 | 100 | Skaggs (1980) |
| Brookston silty clay | 1.5 | 200 | Skaggs (1986) |
| Panoche silty clay | 1.5 | 200 | Chang et al (1983) |
| Cisne silty loam | 1.6 | 60 | Mostaghimi & McMahon (1989) |
| Toledo silty clay | 3.0 | 165 | Skaggs et al (1981) |
| Portsmouth sandy loam | 3.5 | 40 | Skaggs & Nassehzadeh (1984) |
| Coxville loam | 3.5 | 240 | Skaggs (1982) |
| Rains sandy loam | 4.3 | 110 | Broadhead & Skaggs (1982) |
| Wagram loamy sand | 6.0 | 180 | Skaggs (1980) |
| Goldboro sandy loam | 6.5 | 140 | Skaggs et al (1981) |
| Jockvale loamy sand | 7.0 | 20 | Skaggs (1982) |
| Cape Fear loam | 15.0 | 110 | Skaggs (1982) |
| Pocosin peat | 1600.0 | 30 | Konhya et al (1988a) |

rainstorm was 60 cm, then the infiltration parameters would be based on the soil surface layer having a suction of 60 cm.

In a field soil the values of A and B would change during a storm with the downward progress of the wetting front. Thus, the properties of the surface soil layer will control the early infiltration, but once the wetting front has penetrated into the layer below then the properties of that layer will control the infiltration capacity, and so on down the soil profile. The method used in DRAINMOD is simplistic, but it may be argued that all of the current infiltration models have conceptual limitations (such as ignoring seasonal changes in parameters due to plant growth, compaction by machinery and shrink-swell of clays, etc.) or difficulties in determining appropriate parameter input values. The approach taken here is a compromise between a reasonable conceptual model and determinable inputs.

Since the Green and Ampt equation has a physical basis the parameters A and B can be determined from field measurements (e.g. Brakensiek and Onstad, 1977) using a ponding or sprinkling infiltrometer. The latter is to be preferred as it more closely simulates rainfall conditions, but in practice ponding devices are more commonly employed as they are simpler and easier to use. If the infiltration rate, f, is plotted against the inverse of the cumulative infiltration (i.e. 1 / F) then a straight line through the data will fit the equation :

$$f = A\ (1 / F) + B \qquad (5.6)$$

where A is given by the slope of the line and B is the intercept.

When such measured values are not available they may be estimated in a number of ways from basic soil properties. The parameter B equals the saturated hydraulic conductivity (Section 5.2.1). In practice soils are rarely completely saturated in the field due to entrapped air in some of the pores. This may amount to 10% or more of the total pore space (Corey, 1977; Klute, 1986b) but reduces over time with flow of water and dissolution of the trapped air. Bouwer (1969) suggested that the hydraulic conductivity at 'residual air' saturation could be approximated as 0.5 K. The parameter A comprises the product of 3 variables : $A = K\ M\ H_f$ where K may be determined as above, and M is the difference in soil surface water content between the maximum water content (i.e. saturation less entrapped air) and the initial content (corresponding to a suction equal to the height above the water table). The effective suction at the wetting front may be estimated from the soil water characteristic. Bouwer (1969) suggested $H_f$ equals 50% of the air entry value and Brakensiek (1977) suggested $H_f$ is 76% of the bubbling pressure. The air entry value is equivalent to the bubbling pressure since this is the critical pressure at which water leaves, and air penetrates, the soil. If the soil water characteristic is not available for a given soil it may be estimated by matching the soil with one for which the water characteristic is known. Values of parameters including bubbling pressure, saturated water content and wetting front suction have been given for various soil textural classes (Brakensiek *et al.*, 1980; Clapp and Hornberger, 1978). The necessary suction is larger for smaller pores, and values quoted for $H_f$ range from about 10 for sandy soils up to 25-50 cm for clays, silty clays and clay loams, but with a great deal of variation. These are average values and should be treated with caution since other factors than texture may influence them (e.g. structure) at a given site.

If the water table rises to the surface, then the infiltration capacity is set equal to the sum of drainflow and evaporation (the latter is treated as occurring from the soil rather than from the ponded water).

*Water characteristic and drainable porosity*

The soil water characteristic describes how tightly water is held in the soil. It is usually determined in the laboratory using tension tables or pressure plates, and details are given in various texts (e.g. Klute, 1986a). The soil water characteristic may also be approximated from basic soil property measurements (Saxton *et al.*, 1986).

The drainable porosity determines the change in water table elevation when a given amount of water is added or removed. It is based on the difference in water content between saturation and a given suction (for hydrostatic equilibrium this is the suction corresponding to the height above the water table). Drainable porosity may be measured directly using large soil cores or, more usually, estimated from the soil water characteristic for each horizon (Taylor, 1960).

*Hydraulic conductivity*

The saturated hydraulic conductivity of each horizon of the soil above the restricting layer is a very important input. Nevertheless there is a lack of measurements of conductivity, and those values that are available may be subject to considerable experimental error. The most suitable measurements are those obtained in situ. These include the auger hole, slug test and 2- or 4-well methods (Klute, 1986a). The auger hole method is the most widely used, being fairly simple and rapid, although it represents only a single point in the field and may include flows from several horizons. For locations where some field drains already exist, a field effective saturated hydraulic conductivity may be determined from drainflow rates and water table measurements (e.g. Hoffman and Schwab, 1964; Youngs, 1976). This back-calculates K from known flows and hydraulic heads using Darcy's law relationship, and the resulting value integrates the effects of profile heterogeneities, nonuniformities and anisotropy (Skaggs, 1976).

An alternative method of measuring the hydraulic conductivity of a soil is to take an 'undisturbed' soil sample back to the laboratory. Values obtained in this way tend to be smaller than field values as the small samples are often fist-sized soil peds and do not contain cracks, worm holes, root channels etc. In other cases, workers have found much higher values from soil cores than those obtained in situ if the small cores contain macropores which are continuous through the length of the core, enabling short-circuiting of water (Anderson and Bouma, 1973). Furthermore, such cores usually represent vertical conductivity and may be different to the horizontal K values required for the model.

Several studies have proposed estimating conductivity from other soil properties, notably soil texture (Rawls *et al.*, 1982). Such estimates are likely to be prone to considerable uncertainty (Mishra *et al.*, 1989). They do not take account of soil structure and are generally based on conductivity values that were derived from small cores and have all the limitations of such measurements.

*Upward flux*

Upward flux may be described by Equation 5.9 and depends upon the suction profile and the unsaturated hydraulic conductivity. The difficulty in applying this equation is that $K(\theta)$ is usually not known, as it is difficult to measure. A number of methods have been proposed to provide estimates of unsaturated hydraulic conductivity from other, more widely available, soil properties. Perhaps the best approach is based on using the soil water characteristic, itself a reflection of the pore size distribution (Mualem, 1976). For satisfactory results a 'matching factor' is used to force the predicted value at saturation to equal the known saturated hydraulic conductivity. This factor is then applied to the predicted unsaturated hydraulic conductivities. Where the soil water characteristic is not known $K(\theta)$ may be estimated from texture, with the predicted conductivities matched to measured values at saturation (Alexander and Skaggs, 1987). These methods which involve matching to observed values at saturation are clearly not applicable to soils in which flow under saturated conditions is dominated by macropores whilst that under unsaturated conditions is predominantly through the soil matrix. In these soils they should be 'matched' at a lower, 'near' saturation, water content when the larger pores are emptied of water.

For cases where only the soil texture is known, Skaggs (1981) provides generalised relationships directly between upward flux and the depth to the water table for broad soil textural classes. These too, however, require scaling by the saturated hydraulic conductivity.

The rooting depth of the vegetation controls the depth of water extraction to the 'wilting point'. This is usually taken as the depth of most roots, and may be approximated as half the maximum rooting depth of the plants. There is allowance in DRAINMOD for the rooting depth of the plants to vary over the growing season. The wilting point is generally assumed to be 15 bars (1500 kPa). The choice of value is not crucial, since at such large suctions there is little change in water content over a fairly large range in suction.

*Drainage system*

The majority of the input parameters for the drainage system are easy to define, e.g. drain depth and spacing. Three additional parameters have to be calculated or estimated for the Hooghoudt equation. They are the equivalent depth, $d_e$, effective drain radius, $r_e$, and the depth-averaged saturated hydraulic conductivity, $K_e$. These are described in turn.

The equivalent depth is used to account for flow convergence near the drainage pipes (Section 5.2.2). Moody (1967) presented the following equations for calculating $d_e$ :

(a) if $0 < d / L < 0.3$ :

$$d_e = d / (1 + (d / L) [(8 / \pi) \ \ln(d / r_e) - 3.4] \tag{5.11a}$$

(b) if $d / L > 0.3$ :

$$d_e = L \pi / (8 [\ln(L / r_e) - 1.15]) \tag{5.11b}$$

The effective drain radius, $r_e$, is used to account for the additional convergence loss of hydraulic head due to the entry resistance of a finite number of openings in the drain pipe. Drainage pipes are only 'open' to water entry in certain places - between the individual tiles for clay pipes or through perforations in the case of plastic pipes. This results in a certain entry 'resistance' to inflow, with an additional loss of head as water flows to the openings in the drainage pipe. This effect can be approximated in applying the Hooghoudt equation by replacing the actual drain radius r, by a smaller effective radius, $r_e$, in the calculation of the equivalent depth $d_e$. It should be stressed that $r_e$ does not influence the carrying capacity of the pipe (which is defined by the drainage coefficient). Values of $r_e$ have been obtained for a number of different drains using numerical and electric analogue models (Dennis and Trafford, 1975; Bravo and Schwab, 1977). Typical values of $r_e$ for a 4 inch (102 mm) internal diameter drainage pipe are 3 - 4.8 mm for clay tiles, depending upon the gap between the tiles, and 5.1 mm for a corresponding sized plastic pipe with slots. The hydraulic resistance will be reduced by a filter or gravel backfill around the pipe. Thus with a square gravel backfill envelope of cross section length 'a' the effective radius would be 0.59 a. Values are not available for mole drains; such channels have no pipe as such, the mole drain is formed by compaction of the surrounding soil. Leeds-Harrison *et al.*, (1982) demonstrated that storm period flows to mole drains were primarily through mechanically induced cracks and fissures rather than by uniform inflow through the matrix. These cracks will vary between mole drains and over time. In the absence of field measurements the $r_e$ for mole drains was assumed equal to the actual radius of the mole drain. The effect of $r_e$ on $d_e$ is small (Bouwer and van Schilfgaarde, 1963).

The depth-weighted average hydraulic conductivity for the saturated zone is calculated as :

$$K_e = (K1\ d1 + K2\ D2 + ...KN\ DN) / (d1 + D2 + ...DN) \qquad (5.12)$$

where 1, 2, 3 ...N are the soil layers, Kn and Dn are the conductivity and depth respectively of layer n. The water table is here assumed to be at an elevation d1 above the base of layer 1 (d1 < D1).

The grading of the ground surface will affect the amount of surface ponding that must be filled before overland flow can occur across the field. As a very general guide to assessing the surface depressional storage, a field with a relatively smooth surface and on which water does not remain ponded after rain would have 0.1 - 0.5 cm storage (averaged over the field). If there are some shallow depressions, and especially if the land has been cultivated, the surface storage may average 0.6 - 1.5 cm, and for a field with many depressions and widespread ponding after rain, 1.6 - 2.5+ cm (USDA, 1985).

In addition to considering soil water conditions in the field, the DRAINMOD program enables the drain flows to be influenced by the outlet conditions. If desired, the water level in the outfall ditch may even be maintained at a higher level than the field drains, and the resulting head of water causes water to flow from the ditch into the soil via the field drains. This technique, used in the USA, is known as 'subirrigation'. In this study it was assumed that the field ditches could discharge freely into the ditches.

## 5.4 VALIDATION OF DRAINMOD WITH FIELD DATA

It was decided to test the ability of the model to reproduce flows and water table elevations by comparison with the recorded data from the experimental sites discussed in Chapters 3 and 4. Not all of the sites had suitable data for this study, the main limitation being the lack of long time series of computer readable rainfall data for Ballinamore, Tylwch and Staylittle. Although the Ballinamore station had a recording raingauge the data are held in the form of the original charts and it would have been an enormous task to digitize them all. The Tylwch and Staylittle sites had recording raingauges some distance away, requiring separate calibration for each storm event by storage gauges near to the study areas.

The most suitable sites for obtaining data for the model were Grendon (operated by the Institute of Hydrology) and Withernwick (operated by the University of Hull). Both sites were located within research catchments with long-term weather station records and large sets of hourly rainfalls held on computer. Measurements were also available of the soil water characteristic and the saturated hydraulic conductivity. The sites are in areas of high drainage activity (Chapter 2) and are typical of many drainage schemes in the country (Chapter 3). Furthermore, Grendon was in the group of sites where drainage reduced peak flows whilst Withernwick was one of the sites at which drainage resulted in an increase in peak flows (Chapter 4).

Running DRAINMOD for these two sites would therefore be a severe challenge for the model to determine whether it was capable not only of reproducing the observed conditions at each site but also correctly predicting the direction (and if possible the magnitude) of any change in flow response due to field drainage.

### 5.4.1 Site input data

The weather data sets which were used to run the model at the two sites are summarised in Table 5.2. The rainfall regimes are broadly similar, but with slightly higher intensities at Grendon.

*Table 5.2 Hourly rainfall at Grendon and Withernwick, showing the average % time per year that a given hourly rainfall intensity was exceeded*

| | | - Rainfall intensity (mm/hr) - | | | |
|---|---|---|---|---|---|
| Site | Period | >0.0 | >0.5 | >1.0 | >5.0 |
| Grendon | 1/64 - 12/78 | 12.2% | 8.0% | 2.1% | .13% |
| Withernwick | 1/67 - 9/79 | 7.8% | 4.5% | 1.8% | .05% |

The soil input parameters form probably the most difficult set of measurements to obtain, and this study relied heavily on the data collected over many years by the SSLRC. Indeed, if the model is to be applied to an ungauged site then such data would probably be the only ones available - it would be cheaper to drain a field to determine its effects than to conduct a complete study of the soil properties (Trafford, 1977). Some information was already available from the examination of the soil profiles at the study sites, including texture and structure. Further onsite information was available on physical attributes, such as the moisture characteristic and saturated hydraulic conductivity (Tables 3.3 and 3.9). At unsurveyed sites these data could be inferred from more general data. Soil water characteristics, for example, may be obtained from the databank of measurements on the same soil series by the SSLRC (SSEW, 1986).

Estimation of saturated hydraulic conductivity is a bigger problem. Reliable measurements of hydraulic conductivity are difficult to obtain. Values for the saturated conductivity of soils given in textbooks on agricultural drainage generally represent values for broad textural classes, often only for the subsoil. Data for a limited number of soil series have been collected by organisations including the SSLRC and ADAS, but have generally been obtained using auger hole measurements and laboratory analyses of small cores. These techniques are known to be subject to considerable sources of error (Burke *et al.*, 1986). Consequently for the modelling studies such data were used, together with values from the literature (e.g. Paivanen, 1973), to provide initial estimates of saturated hydraulic conductivity in the Hooghoudt and Kirkham equations. These values were subsequently manually adjusted (within the range of published values) to obtain a better model fit to the observed water balance and soil water data. It must be emphasised that there was no optimisation of the model parameters to improve the simulation of the primary interest of this investigation, hourly flow data.

Adjustment of the hydraulic conductivity estimates was felt to be justified by the wide range of recorded values. Indeed, the majority of soil water models use a calibration procedure to fit the observed soil water data (De Jong, 1981). Furthermore, in this investigation the adjustment was confined to the upper horizons of the soil since subsoil values are much more readily available in the literature and much less prone than the topsoil to site specific factors (including weather conditions and land management) influencing soil structure. The rate of upward (unsaturated flux) was not altered from that computed from the initial conductivity values.

The relation between the water table depth and the air volume in the unsaturated zone may be determined from the soil water characteristic by assuming that the profile is drained to equilibrium (with the matric and gravitational potentials equal and opposite). Alternatively the relation between water table depth, air volume and steady state upward flux may be specified in the site data input file. For this study, given the stratified nature of many soils it was felt that it was preferable to use the latter option since this allowed the different properties of the component horizons of the soil to be considered. A suite of data preparation programs has been written to calculate the upward flux and drained porosity of a multi-layered soil from the soil water characteristic and unsaturated hydraulic conductivity (USDA, 1985).

The drainage system parameters were based on the moling or subsoiling since it is the secondary treatment rather than the widely spaced tile drains system which is primarily responsible for the control of the soil water regime.

The values of the equivalent depth, $d_e$, and Kirkham's 'G' were set to -1 (meaning that they would be calculated in the program as described earlier), although of course they could be set to pre-determined values if required.

In some applications DRAINMOD may be used to study the interaction between the flow in the drains and the water levels in the outfall channels. In this study the outfall channels were assumed to be large enough to remove the water discharged into them. The water level in the ditch was set to 100 cm below the ground throughout the year to ensure that it did not interfere with the functioning of the drains. For the 10 cm diameter mole drains the effective radius was taken to be 5.0 cm.

Green and Ampt infiltration parameters were estimated for six initial ground conditions represented by different water table depths. The B parameter was set equal to half the saturated hydraulic conductivity of the upper layer of the soil. When the water table is very close to the soil surface, then this parameter is determined by the ability of the subsoil to remove the water and it is set equal to half the saturated conductivity of the subsoil. The A parameter is calculated from the hydraulic conductivity, fillable porosity (difference in volumetric water content at saturation and at a suction equal to the depth of the water table - computed directly from the water characteristic) and from the wetting front suction.

The model was applied to both the Grendon and Withernwick sites. It was first run for the drained condition (since the drainage system parameters were well defined) and then for the undrained condition.

### 5.4.2 Grendon

The field drainage experiment at Grendon Underwood in Buckinghamshire (Section 3.2.3) has a heavy clay soil belonging to the Evesham soil series. Representative property values for this series from the SSLRC database were used in conjunction with the limited amount of measurements of the soil at the site.

Table 5.3 shows the DRAINMOD site input data file. Weather data comprising hourly rainfall and daily potential evaporation (1964-81 inclusive) were read in from separate files. The potential evaporation data comprise the Penman estimates for short grass calculated for a Meteorological station 1.5 km away by the Institute of Hydrology (Roberts, 1981; 1989). Monthly multiplication factors (only used if the evaporation data are calculated by Thornthwaite's method) were set to unity.

***Model input parameter values***

The drainage system parameters were based on the mole drainage, namely 45 cm deep at 2 m spacings. Although the field contains ridges and furrows these are not 'closed' depressions, and instead lead directly downslope to the outfall ditch. The depression storage parameters selected were 0.4 cm. An initial water table depth of 45 cm was assumed, being the depth of the mole drains. This arbitrary value is of little importance as the model quickly adjusts the position of the phreatic surface.

The onsite soil information comprised the depth to a slowly permeable layer (20 cm) and the 'wet' end of the soil water characteristic (from saturation to 50 cm suction). Since the former was difficult to define, given the ridge and furrow topography at the site, and the latter covered only a limited range of unsaturated conditions it was decided to use the SSLRC database values, but giving consideration to the onsite information.

The average depth to a slowly permeable horizon in the profiles studied by the SSLRC was 24 cm. This was felt to be sufficiently close to the single measurement for Grendon. Accordingly the soil was considered to comprise two layers for modelling purposes : a more permeable horizon in the upper 24 cm of the soil and a less permeable layer below. In addition, for the Hooghoudt equation an arbitrary depth of 100 cm was used for the impermeable base of the soil; the value is not critical at this site as the subsoil is known to have a very low hydraulic conductivity, and any value >60 cm (i.e. $d/L > 0.3$) will not affect the computed value of $d_e$ (cf equation 5.11).

Published values of hydraulic conductivity for clay soils indicate very low permeabilities : 0.04 cm/hr (Castle *et al.*, 1984), 0.02 - 0.08 cm/hr (Farr and Henderson, 1986) and 0.2 - 0.4 cm/hr (Smedema and Rycroft, 1983). Site measurements for Grendon were obtained using a large soil core taken from the 20 - 35 cm deep soil layer. These indicated that the conductivity was very

*Table 5.3 Site input data for Grendon (see text for details)*

GRENDON UNDERWOOD FIELD DRAINAGE SITE WITH EVESHAM SOIL DATA
DRAINED CONDITION

*** PERIOD OF RECORD *** 1964 1 1981 12

*** MONTHLY PE MULTIPLIERS ***
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0

*** DRAINAGE SYSTEM DESIGN (CM) ***

| DEPTH | De | SPACING | D STOR | D C | S STOR | GEE |
|---|---|---|---|---|---|---|
| 45.00 | -1.00 | 200.0 | 0.40 | 10.0 | 0.40 | -1.0 |

| I WT | DITCH D | DITCH S | Rc |
|---|---|---|---|
| 45.0 | 50.0 | 2.50 | 5.0 |

*** MONTHLY OUTFALL DEPTHS (CM) ***

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

*** SOILS (CM,HR) ***

| | | | | | | |
|---|---|---|---|---|---|---|
| 100.00 | | | | | | Restricting barrier depth |
| 4. | 10. | 24. | 1.0 | 100. | 0.05 | Horizon depths and Ksat |

| | | | |
|---|---|---|---|
| 0.00 | 0.000 | 0.2000 | W Table Air vol Upflux |
| 10.00 | 0.062 | 0.2000 | |
| 20.00 | 0.250 | 0.0750 | |
| 30.00 | 0.550 | 0.0170 | |
| 40.00 | 0.910 | 0.0055 | |
| 50.00 | 1.388 | 0.0025 | |
| 100.00 | 5.100 | 0.0000 | |
| 1000.00 | 100.000 | 0.0000 | |
| 6 | | | Green & Ampt parameters |
| | | | W Table A B |
| 0.00 | 0.0 | 0.50 | |
| 14.00 | 1.0 | 0.50 | |
| 24.00 | 2.1 | | |
| 50.00 | 4.2 | | |
| 100.00 | 4.4 | | |
| 1000.00 | 6.0 | | |

*** CROP ***

| | |
|---|---|
| 0.293 | Wilting point |
| 30.0 | Rooting depth (cm) |

sensitive to soil macropores; values below the A horizon dropped from about 0.5 cm/hr at saturation to 0.1 cm/hr at only 0.5 kPa suction and 0.001 cm/hr at 5 kPa (Section 3.2.3). Kneale (1983) studied the hydraulic conductivity of a soil core from the upper 15 cm of the Evesham series and obtained values of 180 cm/hr (saturation), 0.1 cm/hr (1.5 kPa) and 0.007 cm/hr (40 kPa). The very large conductivity at saturation presumably results from the influence of macropore flow, whilst the similarity of the unsaturated conductivities to those for the soil at Grendon reflects the conductivity of the clay peds.

On the basis of these figures, it was decided to choose typical (but conservative) values for the saturated hydraulic conductivity of 0.05 cm/hr for the slowly permeable subsoil layer (below 24 cm depth) and 1.0 cm/hr for the overlying more permeable layer. These values were used in initial runs of the model and for calculating the unsaturated upflux and the Green-Ampt parameter A, which both largely reflect matric flow. Data on soil physical properties were input for two layers, above and below 24 cm, to compute the water table depth, air volume and steady state upflux. There were insufficient data points on the SSLRC water characteristic to derive the air entry value directly, so the wetting front suction (used to compute the A parameter) was estimated as 32 cm, and the wilting point suction water content is that for the upper 24 cm layer at 1500 kPa suction. The rooting depth for the grass was taken to be 30 cm. This was a compromise between a general value for grass of 45 cm (Skaggs, 1981) and 20 cm recorded for the Grendon area (Anon, 1967).

*Simulations of soil water*

The model was first run for the drained condition, and it was found that overland flow was generated much more frequently than observed. Further consideration of the soil profile at Grendon suggested that it was unrealistic to treat the upper 24 cm of the soil as a uniform unit. This was because the surface of the profile at this permanent pasture site comprised a very permeable root mat. As a result a surface layer 4 cm thick (site measurement) was specified having a hydraulic conductivity an order of magnitude greater than that of the underlying soil. With this adjustment the model produced much more realistic results, and the simulated water balance components are summarised as annual totals in Table 5.4a. Overall, actual evaporation accounts for about 68% of the precipitation and drainflow for the remaining 32%. This is in broad agreement with the water balance for the R Ray catchment as a whole; over this period approximately 73% of precipitation was lost as evaporation and 27% as river discharge. The model predicted negligible surface runoff from the drained land, which agreed with observations at the experimental site (Beven, 1980; Robinson and Beven, 1983). The simulated water table was below 30 cm depth for 90% of the time.

The model was then rerun with the same input data except that the drain spacing was increased to 50 m to represent the field boundary ditches of undrained land. The simulated evaporation loss was slightly greater (446 mm cf 429 mm) amounting to 70% of the precipitation (Table 5.4b). The outflow components were very different to those from the drained land, being predominantly overland flow. The water table was at or near the surface for long periods and within 15 cm of the surface for about 32% of the time. Drainage had clearly had a profound effect on the hydrology of the site, with the almost total elimination of the previously frequent and prolonged waterlogging. A full annual water balance was not available for the Grendon field drainage experiment site due to breaks in the data, but these results are supported by observations at the study plots (Robinson and Beven, 1983). The conclusion that drainage altered flow paths rather than the total amount of outflow was also found in a study at Cockle Park (Armstrong, 1983).

*Table 5.4 Annual summaries of modelled outputs (cm) for Grendon site : (a) drained land and (b) undrained land*

| (a) YEAR | RAIN | INFIL | EVAP | DRAINS | S RO | Water table (days) W<15 | W<30 | W<45 | W<60 |
|---|---|---|---|---|---|---|---|---|---|
| 1964 | 50.98 | 49.92 | 43.83 | 10.39 | 1.06 | 1. | 10. | 82. | 130. |
| 1965 | 69.23 | 69.23 | 52.12 | 11.75 | 0.00 | 2. | 26. | 67. | 149. |
| 1966 | 78.90 | 78.77 | 49.10 | 29.96 | 0.13 | 4. | 53. | 159. | 217. |
| 1967 | 68.56 | 68.56 | 49.66 | 19.17 | 0.00 | 1. | 31. | 132. | 169. |
| 1968 | 76.17 | 75.90 | 49.04 | 27.05 | 0.27 | 5. | 45. | 159. | 237. |
| 1969 | 56.00 | 55.64 | 42.71 | 13.13 | 0.37 | 2. | 23. | 86. | 134. |
| 1970 | 63.75 | 63.75 | 40.64 | 22.65 | 0.00 | 2. | 43. | 135. | 169. |
| 1971 | 65.58 | 65.58 | 48.03 | 17.70 | 0.00 | 4. | 28. | 108. | 140. |
| 1972 | 57.61 | 57.61 | 42.53 | 15.47 | 0.00 | 1. | 34. | 109. | 152. |
| 1973 | 46.40 | 46.40 | 46.45 | 3.11 | 0.00 | 0. | 4. | 62. | 81. |
| 1974 | 78.41 | 78.17 | 43.47 | 31.25 | 0.23 | 2. | 42. | 154. | 187. |
| 1975 | 51.74 | 51.74 | 35.99 | 17.02 | 0.00 | 2. | 27. | 104. | 121. |
| 1976 | 47.75 | 47.75 | 27.99 | 17.68 | 0.00 | 4. | 33. | 124. | 173. |
| 1977 | 70.87 | 70.87 | 44.63 | 27.08 | 0.00 | 5. | 44. | 142. | 194. |
| 1978 | 54.35 | 54.35 | 39.40 | 14.93 | 0.00 | 2. | 32. | 91. | 135. |
| 1979 | 74.64 | 73.23 | 39.69 | 33.40 | 1.41 | 5. | 49. | 155. | 199. |
| 1980 | 63.63 | 63.34 | 41.59 | 22.04 | 0.28 | 1. | 44. | 172. | 189. |
| 1981 | 65.30 | 65.30 | 35.63 | 29.36 | 0.00 | 5. | 62. | 192. | 230. |
| MEANS | 63.3 | 63.1 | 42.9 | 20.2 | 0.2 | 3. | 35. | 124. | 167. |
| % Precip : | | 100. | 67.8 | 31.9 | 0.3 | | | | |
| (Ray catchment | % precip | 72.8 | | - - 27.2 | - -) | | | | |

| (b) YEAR | RAIN | INFIL | EVAP | DRAINS | S RO | Water table (days) W<15 | W<30 | W<45 | W<60 |
|---|---|---|---|---|---|---|---|---|---|
| 1964 | 50.98 | 41.65 | 46.07 | 1.11 | 9.32 | 68. | 95.. | 114. | 135. |
| 1965 | 69.23 | 59.48 | 52.12 | 0.69 | 9.35 | 42. | 59. | 79. | 162. |
| 1966 | 78.90 | 54.11 | 51.38 | 2.73 | 24.80 | 162. | 182.. | 197. | 226. |
| 1967 | 68.56 | 54.32 | 52.16 | 2.16 | 14.24 | 130. | 140.. | 155. | 201. |
| 1968 | 76.17 | 51.77 | 49.04 | 2.73 | 24.44 | 167. | 192.. | 227. | 302. |
| 1969 | 56.00 | 44.49 | 45.46 | 1.35 | 11.87 | 80. | 91.3. | 107. | 131. |
| 1970 | 63.75 | 46.99 | 42.79 | 1.88 | 16.41 | 114. | 135.. | 152. | 169. |
| 1971 | 65.58 | 52.32 | 50.52 | 1.80 | 13.28 | 108. | 120.. | 131. | 157. |
| 1972 | 57.61 | 46.34 | 44.69 | 1.77 | 11.60 | 108. | 123.. | 140. | 171. |
| 1973 | 46.40 | 44.46 | 48.37 | 1.03 | 01.94 | 69. | 75.. | 80. | 107. |
| 1974 | 78.41 | 53.27 | 45.63 | 2.58 | 24.87 | 157. | 168.. | 178. | 193. |
| 1975 | 51.74 | 36.43 | 37.49 | 1.68 | 15.58 | 106. | 111.. | 115. | 126. |
| 1976 | 47.75 | 33.42 | 29.34 | 1.33 | 13.93 | 79. | 93.. | 109. | 172. |
| 1977 | 70.87 | 47.74 | 45.61 | 2.13 | 23.21 | 126. | 150.. | 180. | 232. |
| 1978 | 54.35 | 41.14 | 41.57 | 1.47 | 13.53 | 88. | 101.. | 116. | 146. |
| 1979 | 74.64 | 45.30 | 40.94 | 2.46 | 28.98 | 149. | 170.. | 183. | 203. |
| 1980 | 63.63 | 44.54 | 41.59 | 2.95 | 19.14 | 173. | 175.. | 181. | 222. |
| 1981 | 65.30 | 40.59 | 37.76 | 2.83 | 24.70 | 168. | 186.. | 207. | 242. |
| MEANS | 63.3 | 46.6 | 44.6 | 1.9 | 16.7 | 116. | 131. | 147. | 183. |
| % Precip : | | 73.6 | 70.5 | 3.0 | 26.4 | | | | |
| (Ray catchment | % precip | 72.8 | | - - 27.2 | - -) | | | | |

The monthly predictions are shown for 1978 (Fig. 5.5) and indicate a clear seasonal pattern with most flow in the winter period and little or no drainflow for long periods in the summer. This result is in accordance with agricultural experience that artificial drains rarely flow in summer (Smith and Trafford, 1976). The predictions of the seasonal changes in the total air volume in the profile are compared with measurements of profile water content available at the site for that year using the neutron probe method, (Fig 5.6). There is a good broad agreement; both the simulated and observed data show a similar seasonal pattern, and both indicate that the absolute difference in soil water content between drained and undrained land is of the order of 20 mm or less. This may seem a small amount, but it should be remembered that the soil has a low hydraulic conductivity and a regular supply of rain (averaging 180 rain days per year). Nevertheless this relatively modest reduction in water content (increase in water storage capacity) is sufficient to attenuate runoff peaks, given the moderate intensity of the rainfall regime (cf Table 5.2).

### 5.4.3 Withernwick

The field drainage experiment at Withernwick in N Humberside (Section 3.2.5) has a clay loam soil of the Burlingham soil series. Representative property values for profiles of this series from the SSLRC database were used in conjunction with the limited amount of measurements of the soil at the site.

Table 5.5 shows the DRAINMOD input data for the site. Weather data comprising hourly rainfall and daily potential evaporation for a 13-year period (1967-79 inclusive) were used for the simulations. The potential evaporation data comprise the Penman estimates for short grass calculated for a meteorological station about 1 km away.

***Model input parameter values***

The drainage system parameters were based on the subsoiling, namely 50 cm deep at 1.5 m spacings. The values of the equivalent depth, $d_e$, and Kirkham's 'G' were calculated in the program. The fields were very flat, but were ploughed for arable crops and the depression storage parameters values selected were 0.5 cm. An initial water table depth of 50 cm was assumed, being the depth of the subsoiling. The effective radius of the subsoil channels was taken to be 5.0 cm.

The onsite soil information comprised the depth to a slowly permeable layer (45 cm) and the water characteristic. These values were used in conjuction with SSLRC information for a number of other sites with the same soil series. The average depth to a slowly permeable horizon in the four profiles studied by the SSLRC was 46 cm, i.e. almost the same as that recorded at the site. Given this agreement and the availability of a complete soil water characteristic for the site, the onsite profile at the site was used to provide the input data. The upper layers of this soil series are considered to be 'well drained' by the SSLRC; an initial value of 7 cm/hr was chosen. This is in the upper range of published values for clay loam soils : 0.4 - 4 cm/hr (Castle *et al.*, 1984), 0.8 - 8 cm/hr (Smedema and Rycroft, 1983). Consideration of the soil profile at Withernwick suggested that it was unrealistic to treat the upper 45 cm of the

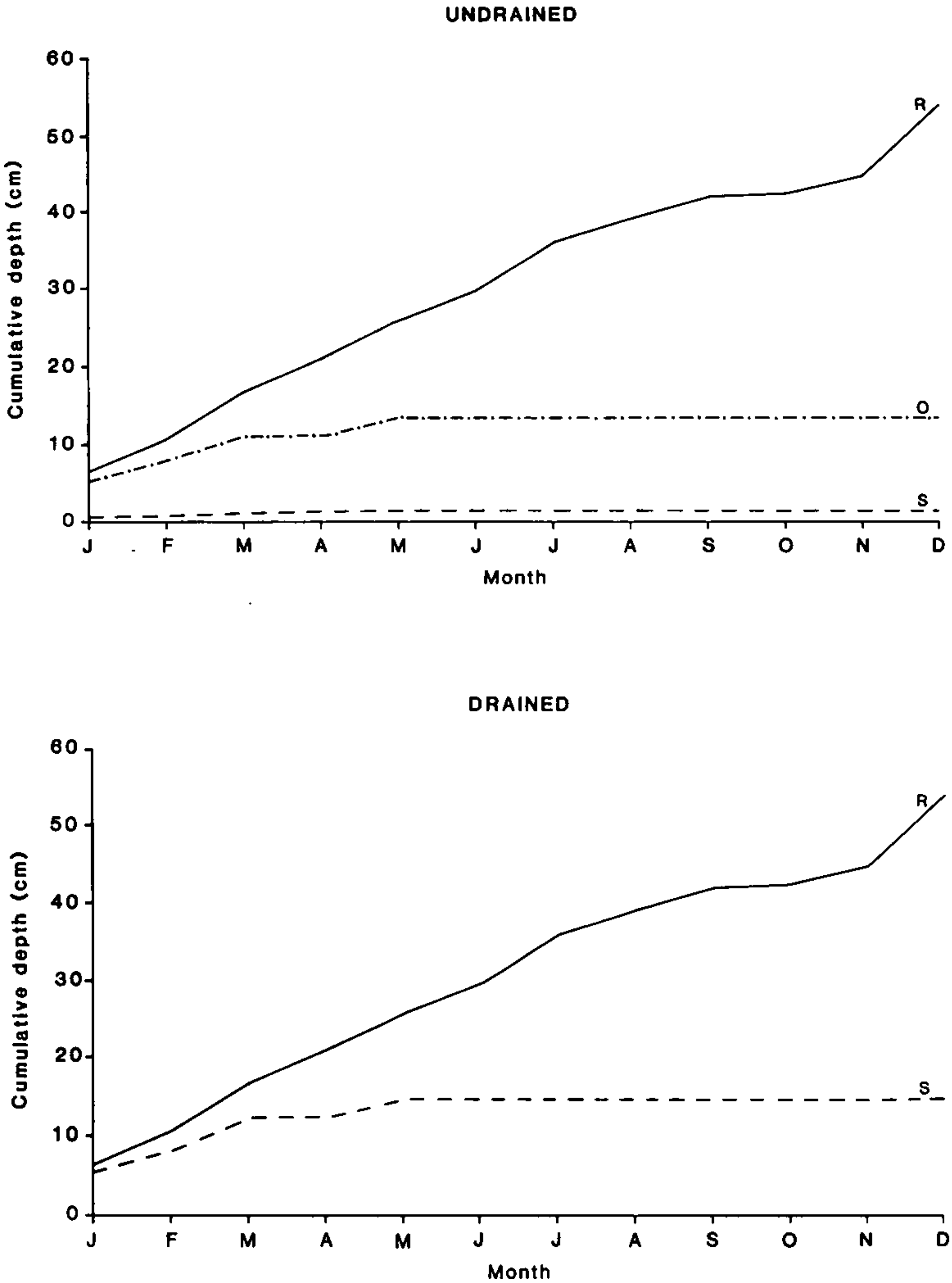



*Figure 5.5 Monthly summaries of modelled outputs (cm) for Grendon site in 1978, showing cumulative rainfall (R), subsurface flow (S) and overland flow (O)*

*Table 5.5 Site input data for Withernwick (see text for details)*

WITHERNWICK FIELD DRAINAGE SITE WITH BURLINGHAM SOIL DATA
DRAINED CONDITION

*** PERIOD OF RECORD *** 1967 1 1979 9

*** MONTHLY PE MULTPLIERS ***
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0

*** DRAINAGE SYSTEM DESIGN (CM) ***

| DEPTH | De | SPACING | D STOR | D C | S STOR | GEE |
|---|---|---|---|---|---|---|
| 50.00 | -1.00 | 150.0 | 0.50 | 10.0 | 0.50 | -1.0 |

| I WT | DITCH D | DITCH S | Re |
|---|---|---|---|
| 50.0 | 50.0 | 2.50 | 5.0 |

*** MONTHLY OUTFALL DEPTHS (CM) ***
100 100 100 100 100 100 100 100 100 100 100 100

*** SOILS (CM,HR) ***

100.00 — Restricting barrier depth

30. 20. 45. 7.0 100. 0.10 — Horizon depths and Ksat

| W Table | Air vol | Upflux |
|---|---|---|
| 0.00 | 0.000 | 0.2000 |
| 15.00 | 0.180 | 0.2000 |
| 30.00 | 0.720 | 0.0800 |
| 45.00 | 1.600 | 0.0200 |
| 50.00 | 2.070 | 0.0120 |
| 60.00 | 3.587 | 0.0060 |
| 80.00 | 6.290 | 0.0020 |
| 120.00 | 9.600 | 0.0000 |
| 1000.00 | 100.000 | 0.0000 |

Green & Ampt parameters

| W Table | A | B |
|---|---|---|
| 0.00 | 0.0 | 0.50 |
| 30.00 | 14.0 | 2.50 |
| 45.00 | 21.0 | 2.50 |
| 50.00 | 23.0 | 2.50 |
| 80.00 | 23.0 | 2.50 |
| 1000.00 | 35.0 | 2.50 |

*** CROP ***

0.170 — Wilting point

30.0 — Rooting depth (cm)

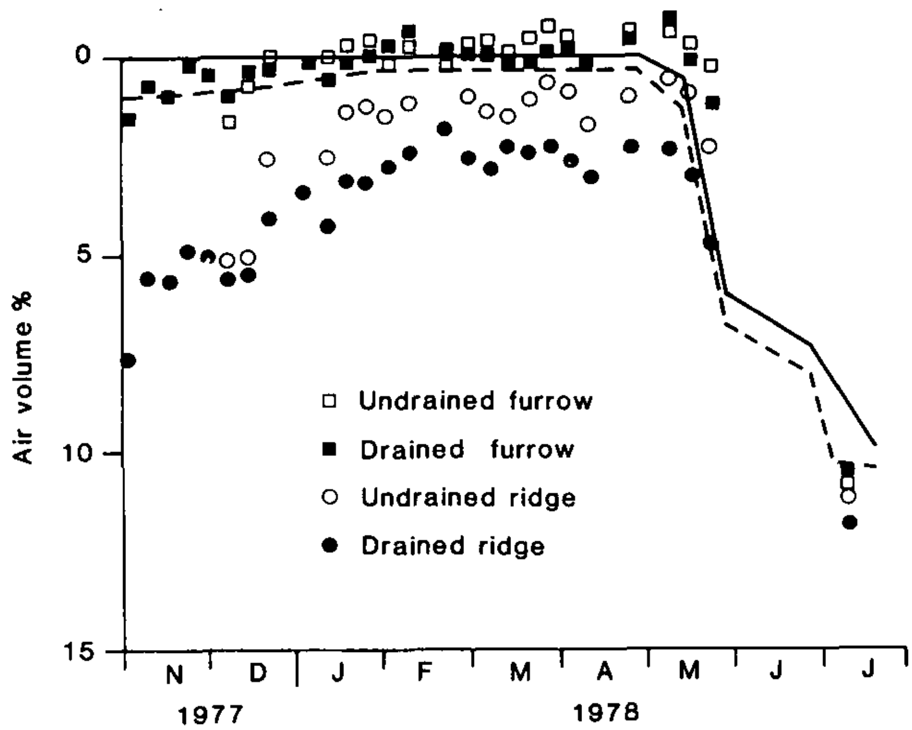



*Figure 5.6 Comparison of measured water content using the neutron probe method at Grendon with DRAINMOD predictions of the air-filled porosity for drained (- -) and undrained (——) land*

soil as a uniform unit. This was because the profile at this arable site had a ploughed horizon, 30 cm thick, with a potentially very high hydraulic conductivity. As a result the upper 30 cm was specified as having a hydraulic conductivity of 20 mm/hr, treble that of the remaining 'well drained' soil layer to 45 cm depth. The saturated hydraulic conductivity of the subsoil below 45 cm depth was estimated to be about 0.1 cm/hr from laboratory measurements of soil cores taken from the site (Robinson *et al.*, 1985) and from field measurements in similar soils elsewhere in Humberside using the auger hole method. An arbitrary value of 100 cm was used for the depth of the impermeable base of the soil. The value chosen is not very critical at this site, any value >45 cm (i.e. d/L > 0.3) does not affect the computed value of $d_e$.

The wetting front suction of this soil texture was estimated as 35 cm, there were insufficient data points on the water characteristic to derive the air entry value directly. The wilting point suction water content is that from the upper 30 cm layer at 1500 kPa suction. The rooting depth for the vegetation was taken to be 30 cm.

*Simulations of soil water*

The model was first run for the drained condition, and the predicted actual evaporation accounted for about 70% of the precipitation and drainflow for the remaining 30% (Table 5.6a). This water balance may be compared with that of the the Catchwater catchment over the same period : approximately 68% of the precipitation was lost as evaporation and 32% as river discharge. Thus the water balance components closely matched those measured for the catchment as a whole. The water table remained deeper than 30 cm for all of

***Table 5.6 Annual summaries of modelled outputs (cm) for Withernwick site : (a) drained land and (b) undrained land***

| (a) | | | | | | Water table (days) | | | |
|---|---|---|---|---|---|---|---|---|---|
| YEAR | RAIN | INFIL | EVAP | DRAINS | S RO | W<15 | W<30 | W<45 | W<60 |
| 1967 | 65.74 | 64.74 | 45.02 | 22.42 | 0.00 | 0. | 0. | 19. | 202. |
| 1968 | 65.21 | 62.41 | 39.78 | 25.86 | 0.00 | 0 | 0. | 26. | 263. |
| 1969 | 75.49 | 75.49 | 41.17 | 34.14 | 0.00 | 0. | 0. | 33. | 210. |
| 1970 | 64.30 | 64.30 | 42.67 | 21.52 | 0.00 | 0. | 0. | 27. | 172. |
| 1971 | 52.09 | 52.09 | 40.69 | 11.30 | 0.00 | 0. | 0. | 13. | 155. |
| 1972 | 49.66 | 49.66 | 38.06 | 11.78 | 0.00 | 0. | 0. | 17. | 167. |
| 1973 | 51.64 | 51.64 | 43.16 | 8.47 | 0.00 | 0. | 0. | 8. | 244. |
| 1974 | 67.53 | 67.53 | 40.74 | 26.82 | 0.00 | 0. | 0. | 28. | 207. |
| 1975 | 52.70 | 52.70 | 35.88 | 16.46 | 0.00 | 0. | 0. | 21. | 177. |
| 1976 | 61.05 | 61.05 | 35.08 | 25.60 | 0.00 | 0. | 0. | 29. | 69. |
| 1977 | 59.55 | 59.55 | 43.53 | 16.81 | 0.00 | 0. | 0. | 20. | 125. |
| 1978 | 65.15 | 65.15 | 43.13 | 21.76 | 0.00 | 0. | 0. | 18. | 144. |
| MEANS | 60.8 | 60.8 | 40.6 | 20.2 | 0.0 | 0. | 0. | 22. | 186. |
| % Precip : | | 100. | 70.0 | 30.0 | 0.0 | | | | |
| (Catchwater | % precip | | 68.0 | - - 32.0 | - -) | | | | |

| (b) | | | | | | Water table (days) | | | |
|---|---|---|---|---|---|---|---|---|---|
| YEAR | RAIN | INFIL | EVAP | DRAINS | S RO | W<15 | W<30 | W<45 | W<60 |
| 1967 | 65.74 | 64.54 | 45.80 | 18.65 | 1.19 | 10. | 60. | 160. | 235. |
| 1968 | 65.21 | 62.41 | 39.78 | 23.24 | 2.80 | 11. | 90. | 196. | 309. |
| 1969 | 75.49 | 73.63 | 41.17 | 32.14 | 1.86 | 24. | 98. | 194. | 221. |
| 1970 | 64.30 | 63.27 | 44.85 | 18.26 | 1.03 | 8. | 61. | 145. | 176. |
| 1971 | 52.09 | 52.09 | 40.69 | 11.38 | 0.00 | 5. | 40. | 132. | 187. |
| 1972 | 49.66 | 49.27 | 38.06 | 11.62 | 0.39 | 3. | 52. | 135. | 216. |
| 1973 | 51.64 | 51.64 | 43.16 | 8.23 | 0.00 | 0. | 37. | 179. | 283. |
| 1974 | 67.53 | 63.96 | 43.12 | 20.95 | 3.57 | 9. | 85. | 180. | 213. |
| 1975 | 52.70 | 52.17 | 38.34 | 15.75 | 0.53 | 8. | 56. | 133. | 158. |
| 1976 | 61.05 | 59.03 | 36.86 | 19.34 | 1.59 | 11. | 72. | 133. | 182. |
| 1977 | 59.55 | 58.69 | 47.24 | 16.03 | 1.29 | 11. | 52. | 95. | 134. |
| 1978 | 65.15 | 62.18 | 43.13 | 15.05 | 2.96 | 11. | 38. | 101. | 161. |
| MEANS | 60.8 | 59.4 | 41.8 | 17.6 | 1.4 | 9. | 62. | 149. | 206. |
| % Precip : | | 97.7 | 68.8 | 28.9 | 2.3 | | | | |
| (Catchwater | % precip | | 68.0 | - - 32.0 | - -) | | | | |

the time, which is in accordance with the limited amount of field measurements.

The model was then applied to the undrained state, using identical soil parameters and changing only the drainage configuration. The same arbitrary spacing of 50 m, used for Grendon, was selected, but in this case the simulated conditions were unrealistic, with predicted soil water conditions far wetter than actually observed; for example, the water table was within 30 cm of the surface for over one-third of the year, and within 15 cm for a fifth of the time.

It is clearly essential that the soil water regime is modelled realistically if the model is to be used to investigate the effect of drainage on flows. As a first approach to improve the fit for the undrained condition at Withernwick, different parameter values were tried for the topsoil. However, it proved difficult to ascribe values to the upper 30 cm plough layer since the properties of such a layer are not reliably known. The effects of cultivation on soil properties and water flows are discussed in Section 8.3.1. As any values of the soil hydraulic properties of the plough layer would necessarily be quite arbitrary it was decided instead to fit the data by altering the arbitrary spacing of the 'boundary ditches'. Halving the spacing from 50 m to 25 m gave a much improved fit to the observed water table data (Table 5.6b). Whilst this spacing is smaller than that for land normally considered to be 'undrained', this figure incorporates the effects of errors in the soil property values chosen (including the porosity and hydraulic conductivity), and is still nearly a 17-fold increase on the drain spacing of the drained land. The monthly water balance predictions are shown in Figure 5.7 for 1974 and 1975.

This exercise has highlighted two important aspects regarding the 'fitting' of a simulation model to a set of observed data, and then applying it to different conditions. Firstly it shows the desirability of obtaining field measurements at the site of interest - either basic soil properties such as conductivity (unfortunately often not available or too disturbed by man's activities), or simpler measurements such as soil water levels, which may enable an effective field value of conductivity to be derived (e.g. Youngs, 1976). Secondly, it highlights the importance of system thresholds in calibrating the parameters of any model. At Grendon the slowly permeable clay soil resulted in the water table rising into the topsoil layer even under drained conditions, and the properties of this layer were important in the modelling excercise. At Withernwick, in contrast, the water table in the drained land rarely rose into the upper layers of the soil, so the properties of this layer were largely 'redundant', playing no part in the simulation. When, however, the model was then applied to the undrained condition, with a higher water table, the properties of this layer were very important, and the values previously used resulted in simulated water table depths that differed considerably from those observed. This necessitated calibrating the model separately to both the drained state (fitting the subsoil parameters) and the undrained state (to fit the topsoil parameters).

### 5.4.4 Comparison of simulated peak flows

Once DRAINMOD gave a satisfactory fit to the available soil water data under drained and undrained conditions at both sites it was then used to generate

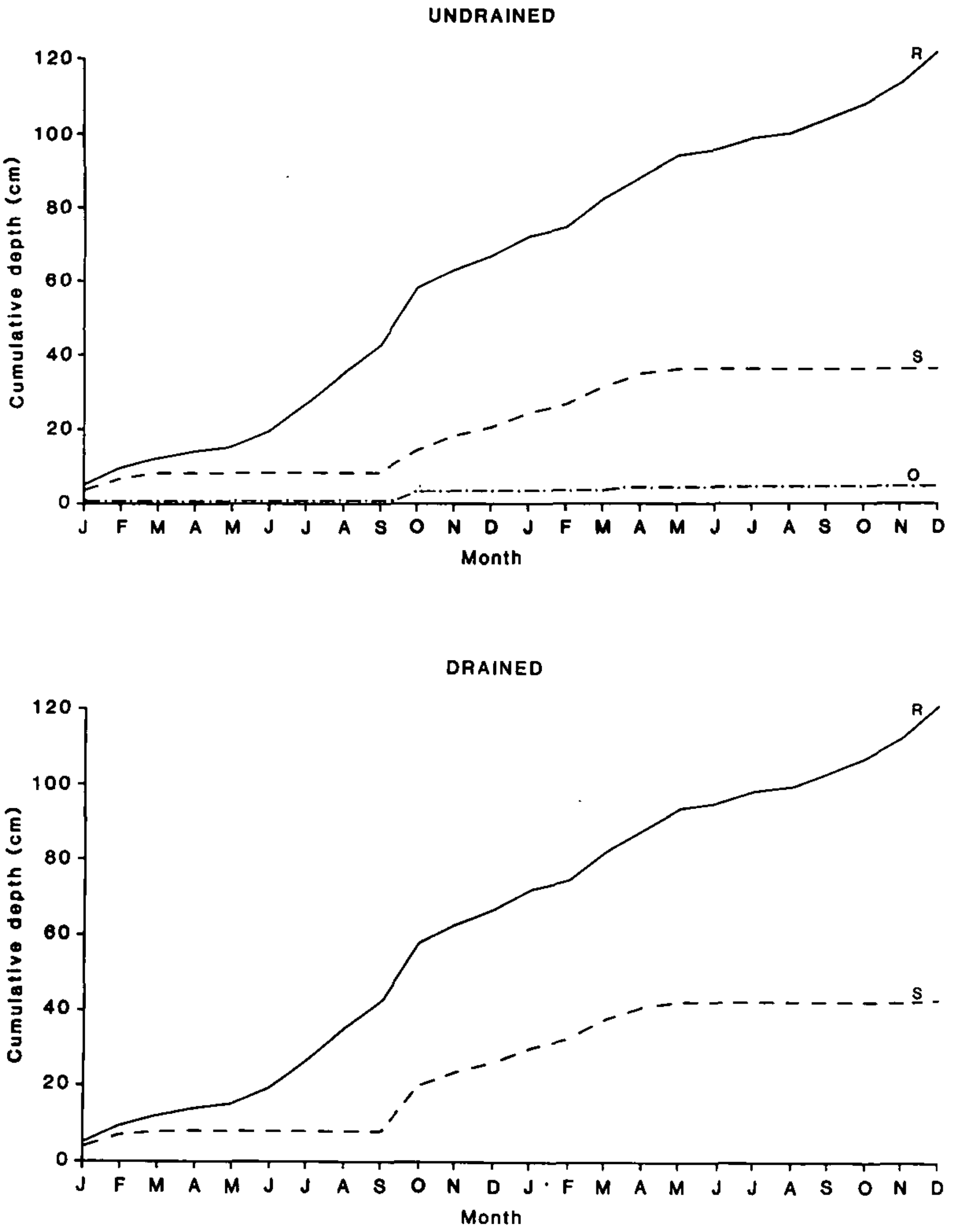



*Figure 5.7 Monthly summaries of modelled outputs (cm) for Withernwick site 1974-5, showing cumulative rainfall (R), subsurface flow (S) and overland flow (O)*

long time series of flows. The peak hourly flows of the simulated hydrographs are compared for each site in Figure 5.8.

These simulations show that at the Grendon site the undrained land generally produces the higher peak flows, whilst at Withernwick the opposite is the case, with higher peak flows from the drained land. This result is exactly in accordance with the observations at the field drainage experiments (Chapter 4). Consideration of the modelled outputs and store contents also throws light on the different mechanisms distinguishing the behaviour of the clay and loam soils.

The reduction in peak runoff at Grendon was achieved by a change in storm runoff mechanism from saturated overland flow, in the undrained state, to subsurface drainflow. This change is shown in Table 5.4. There was a reduction in water table elevation (previously within 15 cm of the ground surface for 116 days per year) to only 3 days after drainage, and the almost complete elimination of overland flow (from 26% of precipitation to 0.3%). The median flow peak was reduced from 0.75 mm/hr to about 0.2 mm/hr.

At Withernwick, the simulated peak flows were higher after drainage; median peak flows increased from about 0.15 mm/hr to 0.21 mm/hr. Storm flow generation was predominantly as subsurface flow (see Table 5.6). The water table was within 15 cm of the surface for only 9 days per year before drainage, and remained deeper than 30 cm for all the period afterwards. Peak subsurface flows were increased due to the much steeper hydraulic gradients that resulted from the closer spaced artificial drains.

Thus both the empirical site studies and the modelling simulation independently show the same influence of soil type : namely drainage generally reduces peak flows from a heavy clay soil, but increases them from the loam soil. It is also worth noting that the model correctly reproduces the relative values of the peak flows from the clay and loam soils. The long-term mean annual flood for the River Ray catchment, which includes the Grendon field site, is 1.16 mm/hr and that of the Catchwater stream, containing Withernwick, is much smaller, only 0.38 mm/hr.

### 5.4.5 Comparison of simulated low flows

The simulation of periods of low flows were also studied. It was found that when the drained and undrained land had similar depths of channels (field drainage pipes or field boundary ditches respectively) the dry weather flows were somewhat higher from the undrained land. Drainage reduced low flows, particularly from the more permeable loam soil. This result is in contrast to the increases observed at the field sites (Section 4.3.4). However, when allowance was made for the generally shallower depth of the boundary ditches on undrained land the simulations indicated that field drainage would increase low flows.

Thus the observed augmentation of low flows by artificial drainage is more a function of the deeper nature of the drains (increasing the available depth of drainable pore spaces) than of the reduction in spacing.

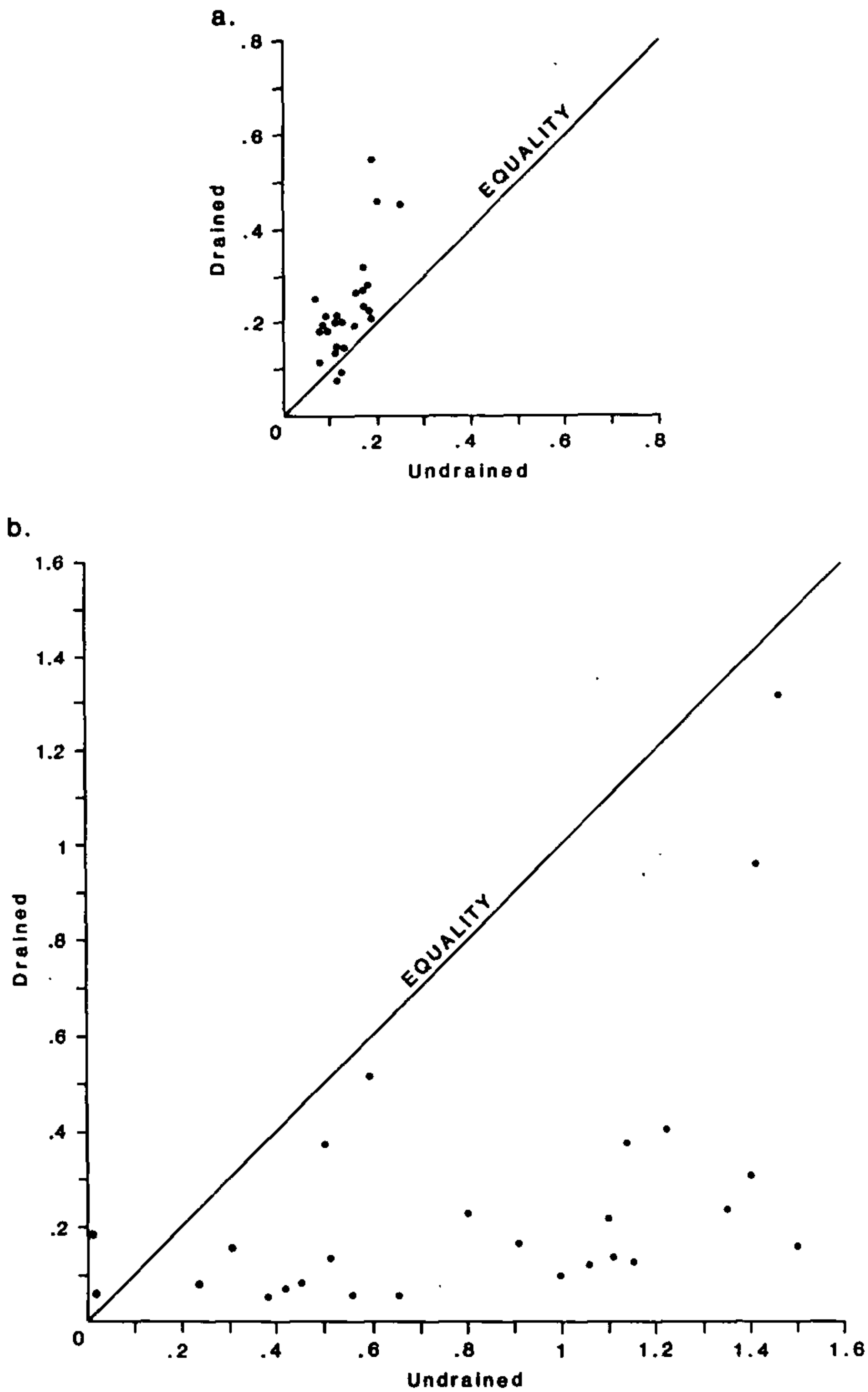



*Figure 5.8 Comparison of simulated peak flows (mm/hr) at (a) Withernwick and (b) Grendon*

## 5.5 EFFECT OF SITE PROPERTIES

The field studies outlined in Chapters 3 and 4 and the modelling work presented in Section 5.4 have shown the importance of soil properties in influencing the effect of artificial drainage on flow regimes. It must of course be recognised that additional factors may be important in particular situations. DRAINMOD was used to investigate the role of some of these, relating to the drainage system and climate.

### 5.5.1 Drainage system

Theoretical and experimental work have shown that the depth and spacing of the drainage system will affect the water table control and drainflow rates. Trafford (1973) quoted unpublished theoretical work by E.C. Childs which showed that as drain spacings are progressively decreased peak flows will at first decrease, but then with further 'drainage development' flows will increase (Fig 5.9). The flows simulated by applying DRAINMOD to the Grendon and Withernwick catchments give a broad confirmation of this pattern. Clay soils lie to the left hand side of the diagram and show a reduction in peak flows with artificial drainage. Loam soils have an inherently higher permeability and lie on the right hand side of the diagram; they exhibit an increase in peak flows with artificial drainage.

Using the results from DRAINMOD, and the observations at the study sites, the pattern shown in Figure 5.9 may be interpreted as follows. As poor

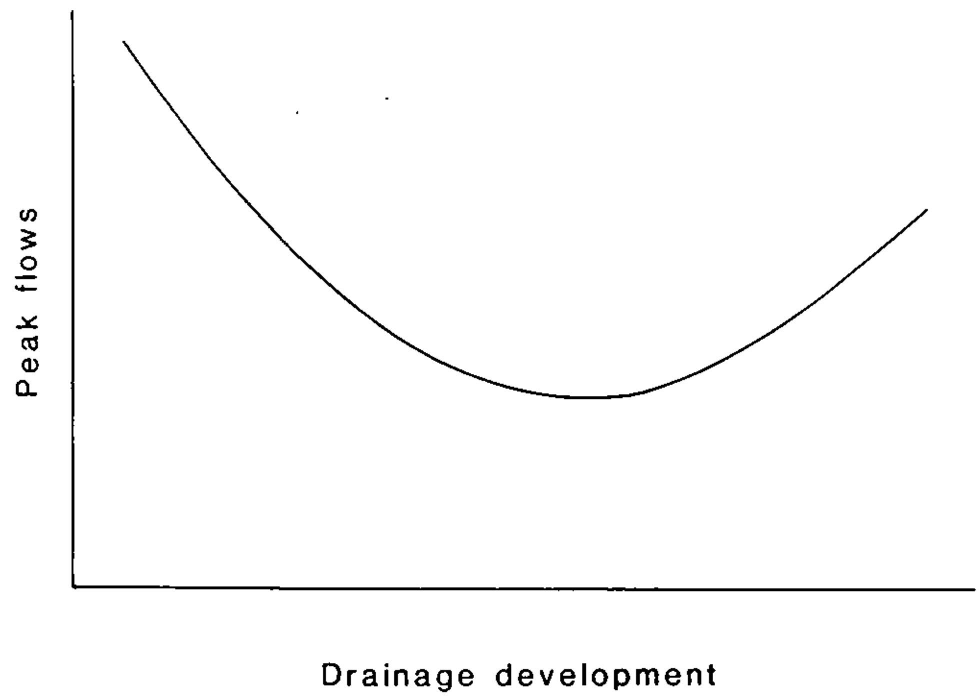



*Figure 5.9 Peak flows for differing degrees of drainage development*

drainage conditions are progressively improved peak flows will first decrease (because surface runoff is reduced), but then any further drainage development will increase peaks as subsurface flow becomes faster. Thus it may be possible that (within financial and agricultural considerations) the careful choice of drain spacing might help reduce peak flows.

The choice of the most suitable depth of drains has been the subject of much debate. In permeable soils deeper drains will give a greater lowering of the water table and may enable a wider drain spacing to be adopted. In contrast, in low permeability soils such as clays there is little water movement in the subsoil, so that all that is needed is to put the drain 'deep enough to be out of harm's way' (Trafford, 1971). Simulations using DRAINMOD confirmed that using a deeper drain depth had little effect on high flows or water tables, due to the very low conductivity of the subsoil.

The discharge carrying capacity of the drainage system (the drainflow coefficient) has not, so far, been considered to be a limiting factor in these discussions. It may need to be taken into account in very large (and rare) storm events, of much greater magnitude than those recorded at the study sites in Chapter 4. If peak flows exceed the capacity of the drainage system then storage and attenuation would result and the conclusions regarding the effect of drainage on outflows might need to be modified.

DRAINMOD does not carry out a full computation of the hydraulic equations of surcharged flow, but does enable some consideration to be given to the storage effect by limiting the drainage rates and backing up surplus water in the soil profile. To determine the likely effect of drainflow capacity on flood peaks DRAINMOD was rerun for the drained condition at both catchments assuming a maximum design flow of 10 mm/day (0.417 mm/hour). This is a fairly typical design value which has been widely used in the lower rainfall areas of the country, although in practice the general use of standard 75 mm diameter clay pipes gave flow capacities that were actually often larger than this value (Trafford, 1971).

The imposition of this drainflow coefficient had a limited effect at Grendon as most drainflow peaks are less than this rate (cf Fig 5.8). In larger events peak flows were generally reduced due to ponding up of water in the soil. The simulations indicated, nevertheless, that when a large storm occurred on very wet ground backing up of soil water could give rise to the complete saturation of the soil profile, and lead to a higher total peak outflow as a result of rapid overland flow to the field outlet ditch of rainfall that failed to infiltrate into the soil.

At Withernwick there was generally sufficient storage capacity in the loam soil to absorb the water that was backed up at times of maximum drainflow, thus attenuating peak rates. This, however, made the soil wetter for the next storm, increasing small peaks, especially in prolonged rainy periods. In a few extreme events, as at Grendon, overland flow was produced (resulting in higher total flow peaks). Overall, the median peak hourly simulated total flow (i.e. drainflow plus any overland flow) was increased by 50% relative to conditions in which the drainflow coefficient was not a limiting factor. The effect of the drainflow coefficient on the peak outflows from a site may be summarised in very broad terms as follows. In the course of a storm (or sequence of storms) high flows at first would be attenuated due to storage of water in pipes and large pores, giving lower maximum flows. Once all the available storage was filled, however, any further rainfall would fail to infiltrate and instead run off the surface of the land. This loss of a storage effect could result in higher peak site outflows (drainflow plus overland flow) than from other drained land which had a larger drainflow coefficient.

It may seem anomalous that a lower drainflow capacity could result in higher peak flows, but this can be seen to result from the restricted evacuation of water from one storm leading to wetter soil conditions for the next storm. The limitation on the maximum flow from the drainage system, taken together with the smaller available soil water storage, could then result during large storms in the backing up of water to the soil surface and the generation of overland flow.

### 5.5.2 Effect of climate

It is to be expected that the amount and frequency of rainfall will affect the available storage capacity of the soil. Thus the impact of drainage on flows could differ between two sites with different climates, even if they were identical in other properties including soils and drainage configurations.

To investigate this, DRAINMOD was run using the site parameters for Withernwick, but with double the recorded rainfall (i.e. increased from 608 mm to 1217 mm per year), which is similar to that at the wetter of the field sites in Chapter 3. The annual potential evaporation was kept unchanged at 470 mm. The effect of the higher rainfall was very pronounced on the simulations for the undrained plot, where the incidence of waterlogging (water table closer to the surface than 15 cm) increased from 9 to 43 days per year (Table 5.7). Surface runoff accounted for 21.3% of the incoming precipitation, and 33% of the site discharge. The median peak flow was four-fold higher. For the drained site the changes were less important, since even with the higher rainfall the artificial drains still largely controlled the soil water regime. Its water table was rarely shallower than 30 cm, and overland flow represented only 1.7% of the rainfall. The effectiveness of the drainage system under these conditions is not surprising, given that similar systems were successfully used in

*Table 5.7 Simulated conditions for Withernwick showing the effect of doubling the observed rainfall on runoff amounts, median peak hourly flow and water table depth*

| Site | Rain (mm) | Runoff (mm) Total | Surface | Qmed (mm/h) | Water table (days) <15 | <30 | <45 (cm) |
|---|---|---|---|---|---|---|---|
| Undrained | 608 | 190 | 14 | .15 | 9 | 62 | 149 |
| | 1217 | 784 | 259 | .60 | 43 | 139 | 241 |
| Drained | 608 | 202 | 0 | .21 | 0 | 0 | 22 |
| | 1217 | 793 | 21 | .52 | 1 | 3 | 45 |

the mineral soils at Tylwch (1300 mm/yr) and at Ballinamore (1100 mm/yr). Peak flows were increased, with the higher rainfall inputs, although by a smaller amount than for the undrained land. This resulted in a 'change-over' in the effect of drainage on peak flows. With a rainfall of about 600 mm/yr artificial drainage increases peak flows, but if the same site had double that precipitation then surface saturation and overland flow would be common in the 'natural' state and the installation of artificial drainage would reduce peak flows.

## 5.6 PREVIOUS MODELLING STUDIES

A number of published studies have used mathematical models to attempt to predict the impact of artificial drainage. The results have been conflicting, some reporting drainage increased peak flows whilst others claimed flood risk was reduced. The following discussion aims to reconcile some of these findings. Due to the complexity that would result in considering different sites and different models this review is confined to cases in which DRAINMOD had previously been used to investigate the effect of agricultural drainage on peak flows (Broadhead and Skaggs, 1982; Konyha *et al.*, 1988; Harms, 1986a,b). Surprisingly, these studies reached dissimilar conclusions.

Broadhead and Skaggs (1982) simulated runoff for five storms on a sandy loam soil and concluded 'on average, good subsurface drainage significantly reduced peak flood flows'. They talked of drainage 'providing a storage reservoir' in the soil, which acted as a buffer to storm runoff. Similarly, Konyha *et al.* (1986) simulated flows for two mineral soils with a shallow organic horizon and concluded the effect of subsurface drainage was to 'reduce the peak runoff'.

In contrast to these simulation results, when Harms (1986a,b) simulated flows from three soil types, sand, sandy loam and clay, he found that peak flows from the loam and the sand were 'significantly increased' by subsurface drainage, whilst those from clay soils were little changed.

It is clearly disturbing that the same model can be used by different authors to reach apparently conflicting results, despite the apparent overlap in the broad types of soils studied; those simulated by Harms included permeabilities both greater and lower than those dealt with in the other investigations. It is perhaps noteworthy that none of these studies had observed data (flows or water table depths) with which to check the model simulations. The main characteristics of the sites given in the papers and used as model inputs have been summarised in Table 5.8. Soil properties were obtained from the literature by Harms and from field sites for the other studies. The spacings used were said by the authors to be typical of those used for 'undrained' field boundary ditches and for drained field pipe systems.

In the study by Broadhead and Skaggs (1982) the simulated water table was at the ground surface on the undrained land, so 'there was little or no water storage available in the soil profile when rainfall occurred'. Field drainage lowered the water table and enabled water to infiltrate into the soil, providing a buffer for rainfall by spreading the runoff over a longer period of time. By this means subsurface drainage significantly reduced peak flood flows. Konyha *et al.* (1988) also found that drainage reduced peak flows in their simulations, and, in

*Table 5.8 Summary of the site characteristics (soil type, conductivity and drain spacing) and runoff from drained and undrained land reported in DRAINMOD simulations by (A) Broadhead and Skaggs (1982), (B) Konyha et al (1986) and (C) Harms (1986a,b)*

| Paper | Soil | K (cm/hr) | Drain spacing (m) | | Surf runoff (% total) | | Effects of drains on flow peaks |
|---|---|---|---|---|---|---|---|
| | | | U | D | U | D | |
| (A) | Loam | 4.3 | 100 | 25 | 90? | 10? | Decrease |
| (B) | Mineral | 1.0 | 100 | 22 | 76 | 23 | Decrease |
| (B) | Mineral | 7.5 | 100 | 33 | 17 | 10 | Decrease |
| (C) | Sand | 25.0 | 300 | 30 | 0 | 0 | Increase |
| (C) | Loam | 1.2 | 200 | 9 | 13 | 2 | Increase |
| (C) | Clay | 0.1 | 30 | 5 | 43 | 27 | No change |
| This study: | | | | | | | |
| | Clay | 1.0 | 50 | 2 | 89 | 1 | Decrease |
| | Loam | 20.0 | 25 | 1.5 | 7 | 0 | Increase |

describing the mechanism responsible, state, 'Subsurface drainage results in a conversion of a significant fraction of the surface runoff into subsurface runoff'. This change can be seen in Table 5.8 where there was a large decrease in the percentage of the total simulated outflow which occurred as overland flow (rather than subsurface flow to the pipe drains or the ditches). The decrease in peak flows was particularly marked for the less permeable soil (K = 1.0 cm/hr) which had the majority of its outflow as overland flow in the undrained state. They were less specific on the magnitude of the reduction in peak flows for the other soil type. The simulation results produced by Broadhead and Skaggs (1982) and Konyha *et al.* (1988) indicate frequent saturation of the soil prior to drainage, and the effect of subsurface drainage was to lower the water table and create an available soil water store. These results broadly correspond with the field drainage experiments on the less permeable soils (Section 4.4) and the simulations for the clay soil at Grendon in this chapter.

This reduction in peak flows supports the conclusion of Chapter 4 that the pre-drainage soil water regime plays a crucial role in determining the direction of the effect of drains upon peak flows. This reduction could not have been predicted solely from the very broad soil descriptions given in the papers : the soil modelled by Broadhead and Skaggs (1982) is simply described as a 'loam', whilst one of the two 'mineral' soils used by Konyha *et al.* (1988) has a hydraulic conductivity of 7.5 cm/hour, although its waterlogged state may be inferred from the fact that it has a 'shallow organic surface horizon'. At the sites considered in these two papers the mean annual precipitation is quite high (about 1250 mm) and this was a major cause of the frequent waterlogging prior to drainage. As demonstrated from the simulation results for Withernwick under different climate regimes (Section 5.5.2), higher rainfall amounts make it more likely drainage will reduce peak flows.

Harms (1986a,b) found that peak flows were increased by drainage of permeable soils. These soils had little or no surface runoff prior to drainage, and the simulations accord with the observations at the field drainage experiments described in Chapter 4 that subsurface drainage increases peak flows from the more permeable soil types. This is also in line with the findings of the simulations in this Chapter, and it may be noted that the annual precipitation used in his simulations averaged about 700 mm/year, which is very similar to that recorded at Withernwick.

In contrast with the experimental studies and model simulations in this and the other papers, Harms (1986a,b) found no change in peak flow frequency with drainage of a clay soil. In his study Harms assumed that drained land had only half the surface depression storage capacity of undrained land (3 mm cf 6 mm), unlike the other papers which held the surface storage parameters unchanged. It appears probable that in Harms' simulations this reduction in surface storage increased the proportion of ponded water which moved as overland flow (rather than being eventually infiltrated or lost to evaporation) and so counterbalanced the smaller quantities of ponded water present.

The apparent differences between the results of these published simulation studies may thus be reconciled, and can be seen to be in complete agreement with both the experimental and simulation studies outlined in this report. All the evidence indicates that the critical factor to be considered is the soil water conditions of the land. If the undrained land is saturated, with little or no available soil water storage capacity, then artificial drainage will result in a lowering of the water table. The creation of an available soil water buffer for storm rainfall and the replacement of surface runoff by subsurface flows (with slower velocities and storage attenuation) will result in lower peak flows than from the undrained land. In cases where storm flows were predominantly by subsurface means, even before drainage, the effect of artificial drainage will be to speed up these subsurface flows and hence increase the resulting peak discharges. At sites where there is still appreciable surface runoff after drainage, or perhaps rainfall intensities exceed the soil infiltration capacity, peak flows will be affected by the available surface depression storage capacity.

Although DRAINMOD was intended to be applied to ungauged sites using 'standard' values for soil properties, it is felt that for the purposes of this study caution must be exercised in such an approach. Rather, that due to the complexity of soil flow processes, DRAINMOD should not be used uncritically solely with 'textbook' values of soil parameters. Site measurements (soil parameters and/or soil water regime) are essential for reliable predictions of soil water conditions and site outflows. For this reason, it was decided that it would be unhelpful, and possibly misleading, to apply DRAINMOD blindly to a large number of hypothetical site conditions with few or no calibration data. Nevertheless, once fitted to a particular site, DRAINMOD appears to be capable of simulating very closely the main elements of the water balance. In the case of Grendon (the only site for which detailed soil water data were available) it gave surprisingly good predictions of the variations in soil water content.

## 5.7 SUMMARY AND CONCLUSIONS

Flows from drained and undrained land were simulated using a computer model fitted to soil water measurements. The results fully support the conclusions of the field experiments that in an overland flow dominated environment artificial drainage reduces peak flows, whilst where subsurface flows predominate drainage will increase peak flows.

The application of this hydrological model has been very useful, both to give insights into the behaviour of the experimental sites at Grendon and Withernwick, and to generalise the results to other areas. In addition to elucidating the effect of soil type, the use of a model has enabled investigation of the effect of drain spacing and climate. It has shown that (other things being equal) drainage is more likely to reduce peak flows in the high rainfall north and west of the country, and to increase them in the drier east and south. The latter areas are those where most drainage activity has taken place this century.

Before these conclusions at the field and plot scale can be transferred to flows at the catchment scale, consideration must be given to the effects of outfall channel improvements. That is the subject of Chapter 6.

# 6 Arterial channels

## 6.1 INTRODUCTION

To extend the investigation from the field scale to the catchment scale it is necessary to consider the role of the outfall ditches and arterial channels into which the field drains discharge. These channels affect the degree of water table control that is possible within a field, and control the routing of the drain outflows to the downstream point of interest.

A great deal more is known about the effects of channel improvements than in-field drainage, both from catchment studies and from hydraulic theory. The purpose of this chapter is to provide background information, and to present some UK case studies indicating the magnitudes involved. Channelisation work is undertaken to reduce or alleviate flooding, to drain agricultural land, to reduce or prevent erosion and to improve navigation. Whilst in terms of economic value the main beneficiaries of land drainage are householders and industry, in terms of land areas protected agriculture is the largest beneficiary (Riddington, 1989). Agricultural drainage is the primary concern of this chapter. Arterial improvement schemes generally aim to modify two aspects of the river system : to lower the water levels in the channel, so that the outfalls of field drains can discharge freely, and to increase the channel conveyance capacity to reduce the occurrence of overspill onto the adjoining flood plain. The relative importance of each aspect will vary from scheme to scheme depending upon its main objectives. In agricultural areas the lowering of river levels may be the main objective, whilst in urban areas the reduction of overbank flooding is of primary concern.

The carrying capacity of a channel depends on a number of hydraulic parameters : the slope (S), cross sectional area (A), wetted perimeter (p) and the roughness (n). The velocity of open channel flow is given by the Manning or Strickler equation :

$$v = [(A/p)^{2/3} \quad (S)^{1/2}] /n \qquad (6.1)$$

where (A/p) is known as the hydraulic radius, generally denoted, R. The discharge (Q) is then given by :

$$Q = A \; [(R)^{2/3} \quad (S)^{1/2}] /n \qquad (6.2)$$

Changes in the hydraulic parameters of a channel due to arterial works can have a major effect on its discharge carrying capacity. Widening and deepening the channel will increase the cross sectional area. The raising of embankments to prevent overbank flooding reduces or eliminates overbank floodplain storage. Straightening a channel will increase the speed of flow by increasing the channel gradient. Arterial channels need regular maintenance, varying from the control of the annual growth of water plants to periodic dredging of accumulated sediment. The removal of weeds and sediment from a watercourse decreases the channel roughness and increases the velocity of flow. A clean straight channel without pools may have a Manning roughness coefficient of, say, 0.03, whilst that of a plant-choked channel may be 0.1; thus a smooth, regular channel may be able to carry up to three times the discharge of a channel of similar cross section and gradient, but with its banks covered with extensive plant growth (Hockin, 1985). The growth of river plants results in a slowing of flow rates especially in low gradient streams and a consequent rise in water levels, and increases in water levels of 30-50 cm have been reported when weed growth has been heavy (Haslam, 1978).

It has long been recognised (e.g. Hillman, 1936; Hogan, 1939) that due to the increase in flow velocities and the reduction in the frequency of overbank storage, channel improvement works may result in an increase in the peak discharges experienced at places further downstream. Emerson (1971) reported an increase in erosion and in the frequency of flooding of the Blackwater River in Missouri, following channelisation work in the upper reaches. Campbell *et al.* (1972) used flood routing models to investigate the effect of channel improvement works. They showed that channelisation speeded up the rate of flood wave movement, and eliminated flooding of adjoining land; there were substantial increases in peak flows. Evans (1984) showed there has been increased erosion downstream of a channelisation scheme on the Great Langdale Beck in Cumbria. Lewin (1976) described how, following the completion of a channel straightening scheme, the increased slope and accelerated erosion may lead to a reversion of the channel form to the original meandering pattern.

Claims that channelisation will reduce the baseflow of rivers are based partly on the argument that such drainage will remove wetland areas, which act as important sources of dry weather flow, and partly on the argument that the associated field drainage will reduce recharge to the underlying aquifer, thereby reducing its contribution to flow in dry weather periods (Newbold, 1977).

## 6.2 CHANNEL WORKS IN BRITAIN

Organised land drainage in Britain can be traced back to Roman times when, for example, the process of reclaiming the Pevensey Marshes was started. The earliest known body in the country responsible for land drainage was the 'Lords, Bailiff and Jurats of the Level of Romney Marsh', which having been in existence from 'time immemorial' was granted a Royal Charter by Henry III in 1252. This organisation was used as the pattern for bodies established to deal with land drainage and sea defences in other low lying parts of England and Wales, which became known as 'commissioners of sewers', the term 'sewer' originally meaning an artificial watercourse. Land drainage law developed in a piecemeal fashion in response to the need to resolve practical problems, and became extremely complex until the Land Drainage Act of 1930 consolidated and simplified the situation. This Act provides the basis of modern land drainage legislation (Wisdom, 1976). It established Catchment Boards which covered the whole of one or more river basins. They had permissive powers to undertake land drainage works on designated 'main rivers'. This work was paid for by a precept on the local councils and Internal Drainage Boards. The latter were constituted under the 1930 Act in addition to the Catchment Boards, and cover many lowland areas liable to flooding and poor drainage.

They usually adopt some of the watercourses in their area on which they carry out regular maintenance as well as capital schemes, and are empowered to levy rates on all properties in their area. Subsequently the Catchment Boards were replaced by River Boards (Rivers Board Act 1948), then River Authorities (Water Resources Act 1963) and then by Regional Water Authorities (Water Act 1973). The Water Authorities carried out maintenance work on some 35,000 km of 'mained' channels in England and Wales (National Water Council, 1982). This comprised about 30,000 km in England (over half in the Anglian, North West and Thames Authority areas) and 5,000 km in Wales. Land drainage responsibilities were transferred to the National Rivers Authority in 1989.

The numerous (> 250), but generally small, Internal Drainage Boards cover about 8% of England and Wales (National Water Council, 1982). They maintain some 27,000 km of intermediate watercourses discharging generally to 'main' river (Robinson, 1984). Local Authorities (County and District) also have powers to carry out land drainage works on non main rivers, but such schemes are few in number and often poorly documented (B.D. Trafford, MAFF quoted in Brookes, 1981). The vast majority of small watercourses and farm ditches are left to be maintained by the riparian occupiers. There are no accurate figures for the total length of such privately maintained watercourses, but those within the areas of the Internal Drainage Boards alone are thought to be of the order of 100,000 km (Robinson, 1984). A survey using data from official records and from drainage engineers indicated that in England and Wales, 1930-80, about 8,500 km of major or capital works schemes were undertaken, mostly on 'mained' rivers and some on watercourses in Internal Drainage Boards districts (Brookes and Gregory, 1983). The percentage of 'main' river channelised by these schemes varies from 40% in the London area (urban protection) to about 10% in the North West (Brookes, 1988).

The situation is somewhat different in Scotland. In the period 1930-80 only 18 arterial channelisation schemes were carried out (Brookes, 1981). This was partly because more responsibility is placed on the riparian owner to propose arterial improvements in Scotland (Penning-Rowsell *et al.*, 1986), and partly because there is much less need for flood alleviation and agricultural improvement schemes since there are not the large floodplain areas which occur in England and Wales.

Arterial works comprise maintenance and capital works. The distinction between them is not always clear on a technical basis, but is defined for administrative purposes according to their funding. Capital works are major improvement schemes and are grant-aided by the MAFF, after being judged to be technically sound and of economic benefit. They include embankments and channel enlargement, and may be expected to have a major effect on channel morphology. Maintenance of river channels on a routine basis is funded by local rates. Since the level of protection is based on a cost benefit analysis capital works are carried out to a variety of standards. Recommended standards for protection of different types of land are given in MAFF (1979). Extensive grazing is given a much lower level of protection from flooding (1 in 1 years) than land producing high value root crops, cereals and grass (1 in 10 years). Higher protection is given for urban properties, normally between 1 in 30 years and 1 in 50 years (Hockin, 1985). Thus, for agricultural schemes the channels may have a design capacity of 1:2 to 1:10 years, and so have little effect on very high return interval floods. A complication to this picture is that, in the past, many channel works were designed to carry a particular discharge, rather than a particular return interval flood.

Maintenance operations vary tremendously, not just between different local councils (on non main rivers), but also between different main rivers. The term 'maintenance' covers both 'light' maintenance, which may be little more than weed cutting, to 'heavy' maintenance which might include excavating, say 0.5m, from the bottom of the channel every 7 years. The latter would obviously have a dramatic effect on channel roughness, but one which would decrease over time until the next round of excavations. Maintenance methods include the clearance of weeds by manual, mechanical and chemical means, the cutting of bank growing plants and the use of excavators for channel dredging (Marshall *et al.*, 1978).

Weed control operations are conducted in about 30% of the total length of main river, and in virtually all the watercourses maintained by Internal Drainage Boards (Robinson, 1984). In addition, dredging to clear silt and weed root accumulations is carried out at intervals typically ranging from every 5 to every 25 years (the frequency depending upon soil type, channel gradient and land use).

Arterial drainage in Britain is increasingly moving towards a care and maintenance role since much of the country is now drained to suitable standards for agricultural protection (Wood, 1981). Furthermore, the combined pressures of food surpluses and nature conservation have virtually eliminated new agriculturally orientated arterial work (Trafford, 1987).

## 6.3 PREVIOUS STUDIES

Whilst there have been comparatively few comprehensive studies of the impact of arterial drainage works in Britain, there has been a great deal of research overseas, particularly in Ireland. This is a result of the great need for land drainage in that country, on account of its topography (comprising a raised maritime rim surrounding a flat interior central plain) and its relatively wet climate (average annual precipitation varies from 800 to 2,500 mm depending upon location).

Arterial drainage works in Ireland date back to the years immediately following the famine of 1845-6. Their purpose was to prevent prolonged inundation in winter and to reduce floods in the summer growing season. Schemes were initially financed by a charge on the improved lands, but from 1945 they were financed by central government enabling the work to be carried out on a much larger scale than was possible before.

Arterial drainage in southern Ireland is carried out in a comprehensive catchment scale, starting at the lower end of the river and working upstream. Channels may be doubled in size. A typical scheme may involve 1,000 km of improved channels together with embankments for flood prone areas, sluices and work on bridges. There are no data on the uptake of field drainage in particular catchments, but the area to benefit is generally about 15% of the total catchment. In one of the earliest studies, Hogan (1939) considered that drainage works on the River Barrow increased flood peaks downstream by 20-25%.

O'Kelly (1945) described the collection of streamflow data for the consideration of the economic sizing of arterial channels. He computed the volumes of overbank storage for various rivers and estimated that the effect of eliminating overbank storage would be to increase peak flows downstream by 12-77%, depending on the area flooded.

O'Kelly (1955) derived a pre- and post-drainage unit hydrograph for the Brosna river at Ferbane, the only catchment which at that time had data before and after a large-scale improvement scheme. Design procedures for arterial drainage schemes were developed from his results by the Office of Public Works (OPW), which is responsible for carrying out this drainage work.

In the late 1970s the OPW undertook a new study for design flow estimation, and by then had data from 12 catchments that had undergone major improvement schemes (Lynn, 1981). The design capacity of the new channels is about the 3-year return interval flood, and it was found that arterial drainage resulted in an average 60% increase in the 3-year return interval peak flow (Bree and Cunnane, 1980; Bailey and Bree, 1981). This was attributed to the elimination of overbank flooded areas and to the increased channel efficiency. The increase was smaller for high return interval floods which would have exceeded the capacity of the new channels. Studies of individual storm events indicated that the higher peaks were due to a change in the timing of storm flows rather than to an increase in the volumes (Lynn, 1981).

In contrast, channel improvement works in N Ireland tend to be somewhat piecemeal, probably reflecting a political decision to distribute investment and employment around the Province. Wilcock (1977, 1979) described the effects of a channel improvement scheme in a 15 $km^2$ catchment. The area has a thick mantle of boulder clay, and there are extensive deposits of peat. About 1.5 km of arterial channel was cleared of bushes and vegetation, and large quantities of sediment were removed. Unfortunately no indication is given of the change in channel dimensions or flow carrying capacity. The study was primarily concerned with the catchment water balance, and did not appear to deal with data at less than a daily time scale. Somewhat suprisingly, given the findings in southern Ireland, Wilcock (1979) found arterial improvements reduced peak flows : 'Channel clearance ... appears to be quite effective in ... reducing the magnitude and frequency of higher flows, particularly in winter'. Whilst low flows were higher in the first year after drainage 'there is, however, no evidence to suggest any lasting augmentation of summer low flows as a direct consequence of channel clearance'. In contrast, Essery and Wilcock (1990) found that low flows were increased following arterial drainage of the upper River Main. They attributed this to inflow from an underlying confined gravel aquifer which became exposed in the bed of the deepened channel.

One of the largest scale European examples of changes in flow regimes due to channel works is provided by the river Rhine. Since the start of the nineteenth century there has been much channelisation and the building of cuts. Flood dykes have been built along the whole length of the upper Rhine; between Basle and Maxau the river length has been shortened by about 70 km, and the natural flood retention area for this stretch of the river has been reduced from 1,000 $km^2$ to just over 100 $km^2$ (Engel, 1985). Growing concern about the effect of these works led to the setting up in 1968 of the Flood Study Commission of the Rhine, which had members from Germany, France, Austria and Switzerland. They used a mathematical flood routing model to compare the observed historic floods (using data as far back as 1876) with flows under conditions of increasing channel development, to show the result of channel development has been to accelerate flood wave velocities and to increase the peak flows. Thus, for example, it was estimated that the recorded flood peak of 4,680 $m^3/s$ on 31st December 1882 at Maxau would have exceeded 6,400 $m^3/s$ (and occurred 3 days earlier) under the current (1982) channel conditions (Engel, 1985). To counter the worsening flood risk it has been proposed that a number of detention basins should be built to act as 'washlands' to store flood waters.

## 6.4 STUDY CATCHMENTS

Following discussions with hydrometry and land drainage staff, several possible study catchments were identified. Factors considered in making this choice included :

a) A long period of reliable flow data before and after the work was carried out,
b) Availability of detailed arterial drainage records (type and date),
c) Qualitative evidence (or claims) of an increase in flood frequency.

In addition to the usual problem of finding catchments with little or no other changes in the period of record, there was a particular difficulty in locating catchments with adequate pre-improvement flow data. Almost by definition, many of the catchments with main channels that were in need of 'improvement' had frequent overbank flooding and submergence or bypassing of the flow gauge. Finally, four catchments in Britain were selected for study. Three had schemes for agricultural benefit and the fourth to prevent flooding of urban development on the flood plain. Most attention is given to the case study of the Witham, since this catchment had data not just on flood peaks but also good records of rainfall.

### 6.4.1 River Witham (Lincolnshire)

In the late 1970s there were a number of very high floods in Lincoln, when the river Witham came close to overtopping its embankments, which would have resulted in widespread flooding of the city. As a direct consequence, a flood alleviation scheme was proposed for Lincoln. Due to the presence of many buildings close to the channel, including a number of historic importance, it was decided against enlarging the channel through Lincoln, and an £8M scheme was designed which involves storing the flood waters in two controlled washlands upstream of the city (AWA, 1984).

Records of river levels at Bargate sluice in Lincoln have been kept since 1963 and show an apparent increase over time in flood peaks (Fig 6.1).

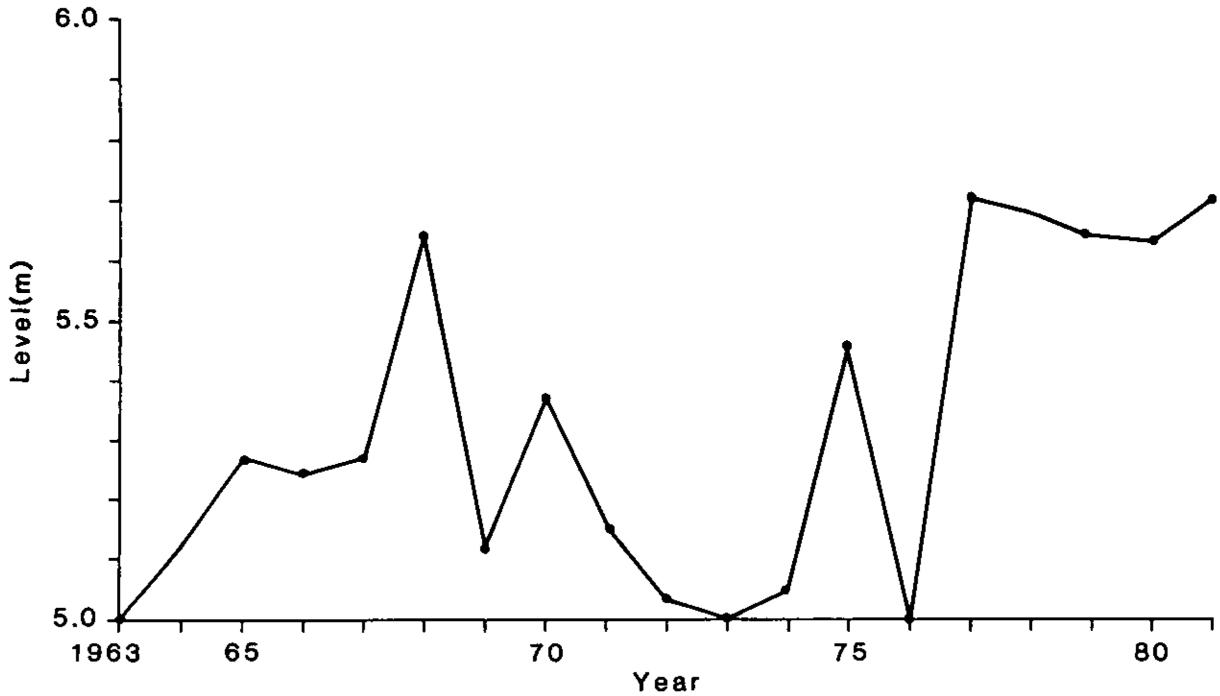



*Figure 6.1 Peak stage levels of the river Witham in Lincoln, recorded at the Bargate sluice*

For hydrological studies, in which flows are related to rainfall, it is preferable to have discharges rather than simply water levels. Unfortunately these data are not suitable to estimate flows since the water level also depends upon the position of the sluice gates and there is some backing up of water at times of high flow from the 'Highbridge', further downstream. The lowest point on the Witham where flows are gauged is at Claypole Mill, 30 km upstream of Lincoln. The catchment area is 298 $km^2$ (draining about 50% of the catchment area to Bargate), and is mainly rural, except for the town of Grantham. The surface geology may be broadly divided into Lias clays downstream of Grantham, and limestone and a small area of gravel upstream.

Flow records at Claypole Mill commenced in January 1959, when a pre-existing old weir was converted to a standard Lea broad crested weir. Importantly, for this study, the station has not been subject to bypassing or drowning out. Records of peak discharges are shown in Fig 6.2, and it is evident that there was an increase in large flood flows in the late 1970s, although there appears to be a cyclical pattern rather than a definite trend. This pattern broadly mirror that of heavy daily rainfalls. A similar conclusion was reached by Arnell (1989) in a comprehensive study of 90 long-term records (1955-84) of river flows in northern and western Europe. He found that there was no evidence of a general progressive trend, but rather periods with greater or lesser floods. Over large areas of western Europe there were few large floods in the early 1970s, with much bigger annual floods in the late 1940s, the late 1960s and the early 1980s. This pattern was evident over large parts of Europe, and appeared to have a climatic cause : 'Years with strong cyclonic patterns tend to give large floods across much of Europe whilst, in contrast, annual maximum floods are smaller in years with strong anticyclonic patterns' (Arnell, 1989).

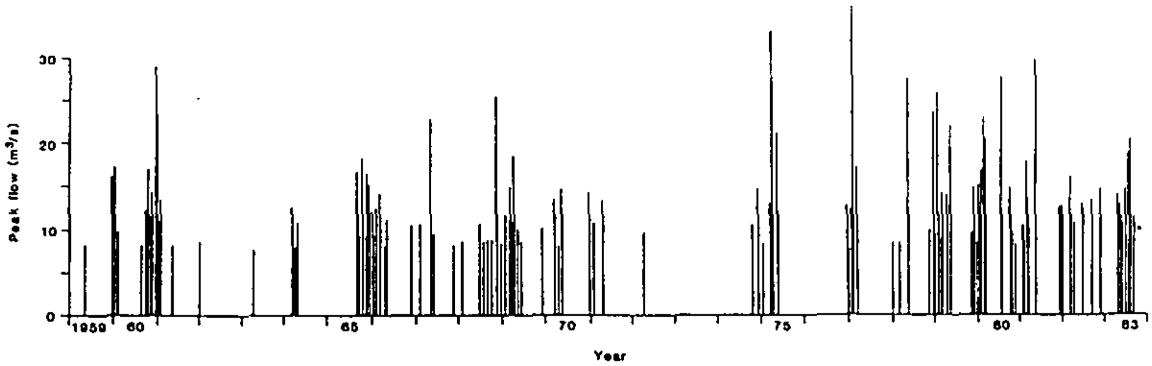



*Figure 6.2 Peak discharges recorded at the Claypole gauging station on the River Witham, 1959-83*

Nevertheless it has been suggested by several authors that anthropogenic factors have played an important role in worsening flood risk of the Witham. These include a change in farming practice from ploughing to minimum cultivation (Brooke, 1983) and arterial channel improvements (Penning-Rowsell *et al.*, 1986).

As part of the design work for the flood alleviation scheme Beran *et al.* (1982) estimated the storage volumes of floods of differing return intervals. This involved using observed and simulated subcatchment hydrographs which were routed down to Lincoln, using the variable parameter Muskingham Cunge method (Price, 1977). In that study an average unit hydrograph was derived for flows at the Claypole Mill gauging station, based on five single peaked hydrographs which occurred in the period 1960-77. It is apparent from an examination of the data used by Beran *et al.* (1982) that the individual unit hydrographs from the later storms were somewhat peakier than those at the start of this period. However, with such a small sample size, it would be difficult to draw any definite conclusions.

Brooke (1983) was concerned that the flood risk might be increasing over time and that any protection scheme based on the 'current' situation could subsequently prove to be inadequate. She studied the largest daily rainfalls and the annual maximum flood peaks at Bargate and Claypole for evidence of non-stationarity, and found a similar decline in both rainfall and flows in the early 1970s followed by a return to the levels of the 1960s by 1980, but apparently felt that rainfall variations did not account for all the temporal pattern of flood peaks. To investigate this further she correlated the largest 21 floods at both sites with a range of variables including the preceding daily rainfall as well as several representing 'anthropogic' influences. These comprised the length of arterial improvements (from AWA records), changes in the urban areas (from large-scale maps) and areas under minimal cultivation (estimated from a postal questionnaire to a sample of local farmers). Rainfall was not a statistically significant variable, due perhaps to the differences in antecedent conditions, as well as the difference between storm rainfall depths and falls in 9am - 9am 'rain days'. Of the correlations between the flood peaks at both sites and the human influences, the area of minimal cultivation gave the slightly higher correlation, and was chosen by Brooke as the main 'cause' of the apparent increase in peak flows, although acknowledging that 'Substantial channel improvements have been made on the Upper Witham and its tributaries, and to some extent, these are bound to increase channel efficiency'.

Minimal cultivation, instead of conventional deeper ploughing was considered to increase the risk of surface compaction and lead to higher peak rates of runoff. This process could have serious consequences because if the change from ploughing to minimal cultivation of arable farmland continued then the trend to increasing frequency of flood peaks would also continue. The effects of management practices on discharges are discussed in more detail in Section 8.3.1.

Brooke's estimates of the proportion of the catchment with minimal cultivation (about 30-35%) appear reasonable; in the absence of actual records it is estimated by MAFF staff from their local experience that about 30-50% of the farmland in the catchment is subject to minimal cultivation. Her statistical approach needs some qualification, however, since in dealing with the anthropogenic factors she had only three independent time values of the extent of minimal cultivation (pre-1970, 1970-75 and post-1975), and used not the 21 largest peaks, but a 6-year moving average of the annual maximum flood peaks. Both these aspects considerably reduce the numbers of 'degrees of freedom' in the statistical tests adopted, and hence lower their true 'significance' level.

An alternative explanation for the observed increase in flood frequency was offered by Penning-Rowsell *et al*, (1986; p103), although they gave no quantitative analysis or evidence to support their conviction that 'upstream river improvements giving flood protection to agricultural land appear to mean that the historic pattern of floods spreading on to rural washlands has been replaced by the bulk of floodwaters passing downstream to affect Lincoln'.

Much of the catchment is good quality agricultural land (MAFF grades 2 and 3) and extensive channel improvements were carried out primarily to reduce the incidence of river flooding of this land, and to provide deeper outfalls for field drains. In addition, there are extensive embankments of excavated material along both channel banks giving total channel discharge capacities nearer to the 1:50 year flood. Although the banks have gaps for roads etc, much of the high flows would nevertheless be contained between them. The channelisation was carried out by working upstream from Lincoln and was largely completed by 1974, with the channel enlargement through Grantham completed in 1978. Figure 6.3 and

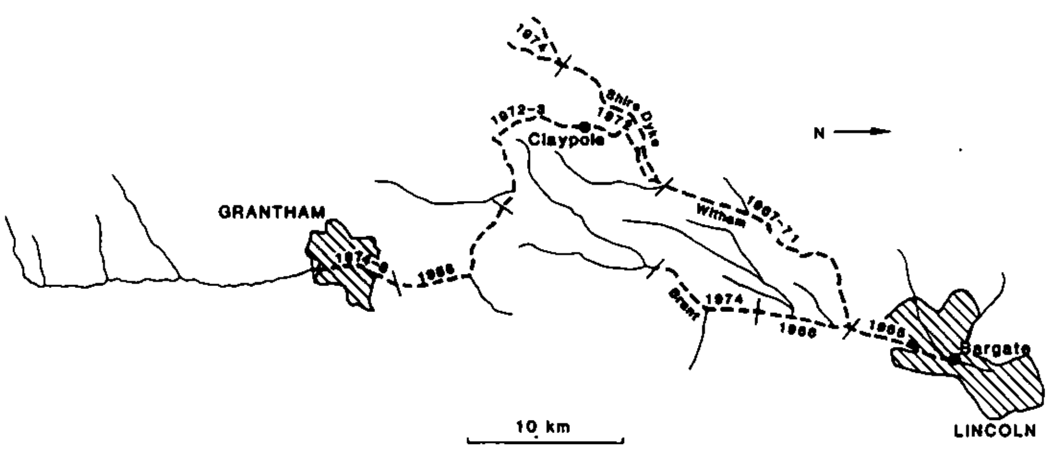



*Figure 6.3 Location and timing of river Witham channel works*

Table 6.1 indicate the location and timing of the channel works for the Witham catchment upstream of Lincoln. The data were abstracted from manuscript records held by the NRA in Lincoln of work conducted by the Lincolnshire River Board (pre-1969), Lincolnshire River Authority (1969-74) and Anglian Water Authority (post-1974). The works mainly comprised deepening and widening the channel, and the construction of the flood embankments.

*Table 6.1 Channel improvements on the River Witham upstream of Lincoln (* denotes upstream of the Claypole flow gauge; N/A = information not available)*

| Name of reach | Date | Length (km) | Channel capacity ($m^3/s$) Before | After |
|---|---|---|---|---|
| * Hougham - Belton | 1955 | 9.3 | N/A | 25-29 |
| Brant - Shire Dyke | 1967-71 | 18.7 | N/A | 40. |
| Shire Dyke | 1972 | 8.5 | N/A | 6.0 |
| * Shire Dyke - Hougham | 1972-73 | 15.6· | 13.2 | 31.4 |
| * Grantham | 1974-78 | 4.2 | 14-20 | 37-40 |
| * S Witham | 1970 | 0.6 | N/A | 2.7 |

To determine whether the increase in flood frequency was a chance pattern, the whole period of record was examined for large events, to yield a total of 20 events over the period October 1960 to January 1988 for unit hydrograph analysis. A one-hour time interval was initially used, but the derived unit hydrographs were so flat topped that it was impossible to objectively define a time to peak flow. The analysis was repeated using a three-hour data interval (Table 6.2).

Figure 6.4 shows the change in the unit hydrograph time to peak values (here expressed as for a one-hour unit hydrograph). There was a clear change in

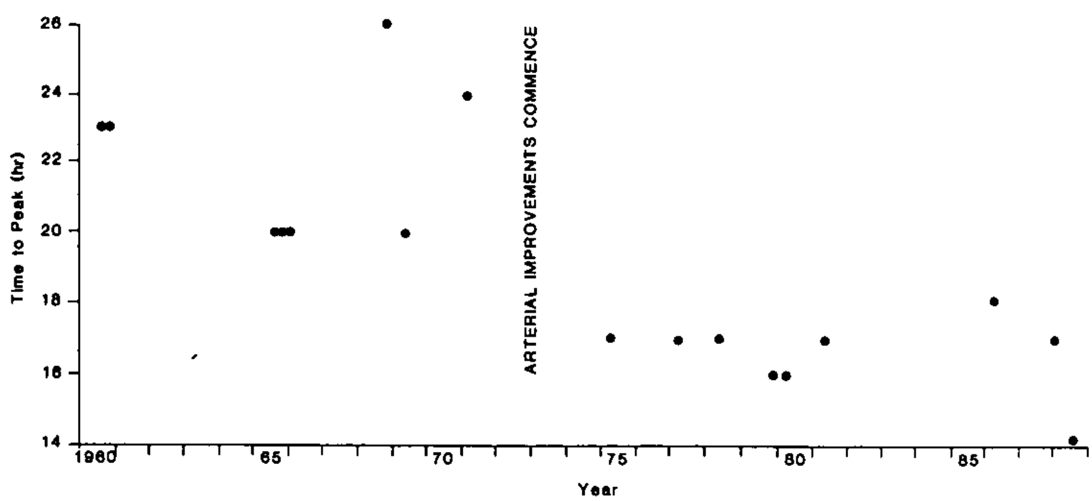



*Figure 6.4 Unit hydrograph time to peak values at Claypole, for large events in the period 1960-88*

the unit hydrograph parameters to a quicker, peakier, response; the time to peak was reduced (statistically significant at 0.001 level) and the peak ordinate was increased (just failed at 0.10 level). The percentage runoff in storm events did not alter significantly. The change in storm runoff timing was not gradual, as would be expected if it was due to the cumulative effect of many individual farmers changing to minimal cultivation (cf the rate of uptake of field drainage in Section 7.4.1). Rather, it was more of a 'step change', taking place over a period of only a few years, with a stable set of values both before and afterwards.

*Table 6.2 Storm runoff events and three-hour unit hydrographs for the river Witham at Claypole Mill, 1960-88. Tp and Qp are the time to peak (3*hours) and peak ordinate ($m^3/100\ km^3$) respectively*

| Date | Peak flow ($m^3/s$) | Percentage runoff | FSR Lag (hrs) | Unit hydrograph Tp | Qp |
|---|---|---|---|---|---|
| 29/10/60 | 16.8 | 25 | 22.4 | 8 | 8.5 |
| 3/12/60 | 29.1 | 37 | 31.5 | 12 | 6.3 |
| 18/12/60 | 23.9 | 27 | 18.2 | 8 | 7.5 |
| 28/11/65 | 17.2 | 20 | 20.8 | 7 | 8 |
| 9/12/65 | 18.7 | 31 | 20.3 | 7 | 7.3 |
| 18/12/65 | 16.8 | 17. | 19.5 | 7 | 10.4 |
| 13/05/67 | 23.3 | 31 | 32.7 | - | - |
| 1/11/68 | 26.4 | 25 | 26.3 | 9 | 7.2 |
| 5/05/69 | 19.3 | 18 | 21.4 | 7 | 9.7 |
| 22/01/71 | 13.8 | 15 | 13.8 | 8 | 11.2 |
| 8/03/75 | 33.0 | 30 | 18.4 | 6 | 9.1 |
| 9/02/77 | 37.5 | 34 | 22.3 | 6 | 8.0 |
| 5/05/78 | 27.5 | 27 | 16.2 | 6 | 8.6 |
| 27/12/79 | 14.6 | 18 | 11.7 | 5-6 | 10.3 |
| 23/02/80 | 23.3 | 30 | 16.1 | 5-6 | 10.0 |
| 9/03/81 | 17.7 | 31 | 19.0 | 6 | 7.8 |
| 23/04/81 | 29.0 | 48 | 25.8 | - | - |
| 1/02/86 | 15.3 | 32 | 18.7 | 6-7 | 7.2 |
| 20/10/87 | 17.1 | 23 | 17.1 | 5-6 | 9.1 |
| 1/01/88 | 17.9 | 22 | 17.9 | 4 | 13.9 |

Comparison of Fig 6.4 with Table 6.1 indicates that this change coincided with the period when the majority of the channel improvement works were carried out. This suggests that channelisation was the primary cause of the change in flood response, and this conclusion is supported by an analysis of the individual storm parameters. Figure 6.5 shows that before this change took place there was a negative correlation between peak storm flow and the unit hydrograph parameters. This may represent the greater attenuation of bigger hydrographs due to more overbank flooding and storage (all of the peaks are greater than the estimated pre-improvement channel capacity). This relationship was much weaker after the channel improvements. Archer (1989) described similar flood wave attenuation on the River Tees in Northumbria, due to overbank flooding and storage of water.

The change in flow regime is apparent in the peak flow record (Table 6.3). Due to the relatively short time series of data that are available when they are divided into sub-periods the partial duration series of flood exceedences were examined in addition to the annual maximum flows. The numbers of exceedences were counted above different discharge thresholds. It is evident that there has been an increase in both the number of floods and their magnitude between 1959-66 and 1974-83 (the latest available data). The increases were particularly marked for the larger threshold events. Peak flows (> 8 $m^3/s$) increased by

*Table 6.3 Peak discharges of the Witham at Claypole ($m^3/s$)*

| Period | Peaks > 8 $m^3/s$ mean | s. d. | num/yr | > 10 $m^3/s$ num/yr | Annual max mean | s. d. |
|---|---|---|---|---|---|---|
| 1959-66 | 12.8 | 4.6 | 4.8 | 3.3 | 15.6 | 7.1 |
| 1974-83 | 15.4 | 6.9 | 5.3 | 4.3 | 27.2 | 6.3 |
| Sig level | NS | - | NS | .15 | .10 | - |

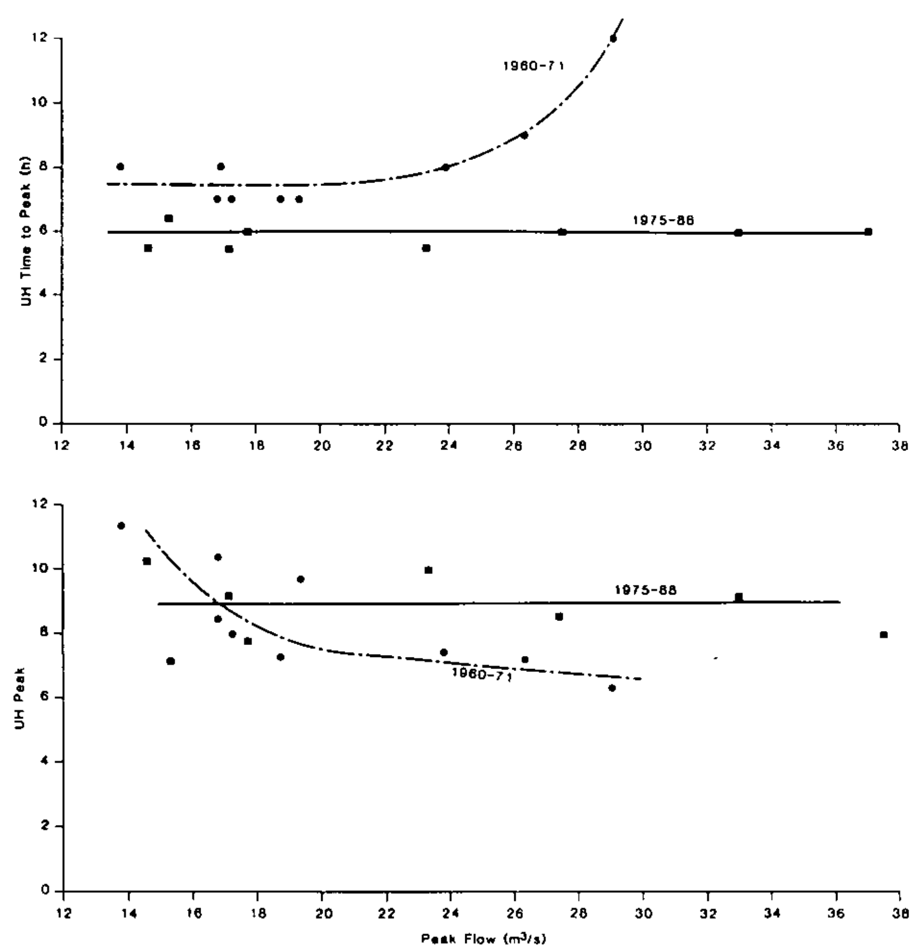



*Figure 6.5 Relation between unit hydrograph parameters and flood magnitude at Claypole, before and after the upstream channel improvements*

about 20% whilst the annual maxima increased by a much larger amount (over 70%) due to their greater overbank flooding and attenuation prior to the channel improvements (cf Fig 6.5).

The statistical signifance levels are based on the Mann Whitney test for the differences in flood magnitudes and a Poisson model for the number of exceedences. If it is assumed that the number of flood peaks can be described by a Poisson distribution (cf Cunnane, 1973) then the difference in the rates of occurrence between two periods may be tested (Cox and Lewis, 1966). Using the normal approximation to the binomial distribution, with a continuity correction, yields the test statistic :

$$Z = [\,|n - N\theta| - 0.5] \,/\, \sqrt{[N\theta - (1 - \theta)\,]} \qquad (6.3)$$

where n is the number of exceedences in the first period and N is the total number in both periods; θ is the duration of the first period as a proportion of the complete record length. This statistic compares the deviation of n from its expectation, Nθ, with its standard error. Confidence intervals can be read from standard normal tables.

The nearest catchment of a similar size to the Witham at Claypole, with flow records dating back to 1959 is the river Glen at Kates Bridge (342 $km^2$), about 40 km south of Claypole. There was no significant change in the frequency of peak events at this station between these periods, but an increase in the mean annual flood of about 36%. In the absence of known artificial causes this may be interpreted as the result of fluctuations in weather conditions.

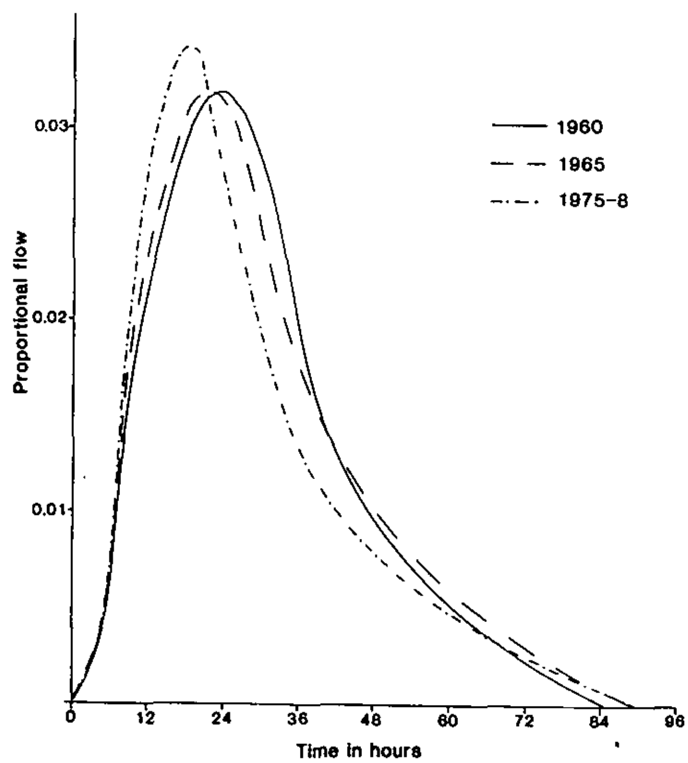



*Figure 6.6 Average three-hour unit hydrographs, at Claypole, showing the increase in flow response over time*

Deriving an average unit hydrograph at Claypole for the storm events before and after 1974 illustrates the change in reponse as a result of the channel improvements upstream (Fig 6.6).

Since there were further channel improvement works downstream of Claypole, the next stage was to compare the timing of flood peaks at Claypole and at Bargate in Lincoln to look for changes in the flood wave travel speed down this part of the River Witham. An analysis of 35 flood events, 1964-80, showed no significant change in peak travel times despite the intervening channel improvement works known to have taken place at that time. Although somewhat suprising at first, this can be attributed to several factors. Firstly, it proved very difficult to define the time of the peak water level at both sites due to the very flat 'tops' of the storm responses, particularly at Bargate. Secondly, the levels at Bargate were influenced by manual adjustments to the sluice gates at times of high flows to allow water down the Sincil dyke relief channel. The sluice was usually opened on the rising limb, before the peak, and would have affected the water level.

Thirdly, there is a large additional contributing area (some 300 km$^2$) downstream of the Claypole Mill (298 km$^2$) to Bargate.

In presenting these results which show an increase over time in the peak flows on the river Witham, it should be noted in the wider context of flooding at Lincoln that the design of the Lincoln flood alleviation scheme was based on storm hydrographs routed according to the dimensions of the post-improvement channel (J. East, NRA pers. comm.).

### 6.4.2 Barlings Eau (Lincolnshire)

This catchment (210 km$^2$), a northern tributary of the river Witham, is situated 12 km to the north east of Lincoln. The main stream drains the dip slope of the Lincolnshire limestone. The catchment geology comprises about 30% limestone and 65% clays. The agricultural quality of the land is MAFF grade 3. Parts of the area suffered from overbank flooding and from poor drainage due to the high water level of the Barlings Eau. A comprehensive channel improvement scheme was carried out in 1978 involving extensive deepening and widening of about 10 km of channel, increasing its discharge capacity from the 1 in 3 year flood to the 1 in 10 year flood (about 28 m$^3$/s). Discharge measurements commenced in 1960 at a velocity area station, rated by current meter. A new flat V weir was built in the improved channel in 1980.

Table 6.4 shows a large increase in peak flows following the channel improvements, particularly for the bigger events. Peaks > 10 m$^3$/s were about 25% greater on average and the annual maxima were 35% higher. In contrast, on another tributary of the Witham, the river Bain at Fulsby Lock (197 km$^2$), the mean annual maximum fell by 12% between these two periods. It must be noted, however, that the flow rating for the new weir on the Barlings Eau may over-estimate high flows In recent years, due to a policy of reduced expenditure on channel maintenance work, extensive weed growth has resulted in a large scatter in the stage discharge relation even at high flows, and the flow data have become less reliable. Despite these problems with the data

*Table 6.4 Peak discharges for the Barlings Eau*

| Period | Peaks > 10 $m^3/s$ mean | s. d. | num/yr | >12 $m^3/s$ num/yr | >15 $m^3/s$ num/yr | Annual max mean | s. d. |
|---|---|---|---|---|---|---|---|
| 1960-77 | 16.8 | 4.7 | 4.6 | 3.7 | 2.5 | 20.4 | 5.7 |
| 1980-84 | 21.1 | 6.6 | 5.9 | 5.5 | 5.5 | 27.5 | 8.4 |
| Sig level | NS | - | NS | .05 | .01 | .10 | - |

there was sufficient evidence to indicate that the arterial scheme had increased the flood response. The FSR 'lag' time between storm rainfall and peak flow (or river level) is independent of the rating curve and indicated a reduction in response time from 16 to 10 hours.

### 6.4.3 River Ock (Oxfordshire)

This mainly rural catchment, south west of Oxford, 240 $km^2$ in area, lies mostly on impervious clay soils. The area was known locally by farmers as the 'Black country' due to its poor outfalls, heavy soils and frequent and prolonged waterlogging Flow records commenced in 1962 at an existing broad crested weir which was calibrated by current meter. The catchment has a very responsive storm runoff, but due to frequent overbank flooding bypassing of the gauge occured at floods greater than 10-12 $m^3/s$ down the adjacent, lower, Sandford Brook.

Due to the poor natural drainage, an arterial channel improvement scheme was carried out from 1977-86 to enable agricultural field drainage to be installed. It comprised channel enlargement and regrading with few or no flood embankments. The work commenced at the lower end of the catchment and continued upstream (Fig 6.7), although due to problems of access some sections were done out of sequence. This scheme is probably the last big agricultural drainage improvement scheme in the Thames region (C. Candish, NRA pers. comm.).

In 1979 a new weir was constructed on the improved channel. The new channel contains flows up to the 1:10 year flood (17 $m^3/s$), whilst the old channel had overbank flooding about once every 2 years. Peak flow records are summarised in Table 6.5. There appears to have been an increase, but there are unfortunately insufficient data since the completion of the scheme to properly assess its impact on flows.

### 6.4.4 River Ewenny (Mid-Glamorgan)

The river Ewenny near Bridgend provides, perhaps an extreme example of the effects of a flood alleviation scheme. It comprises a 63 $km^2$ lowland

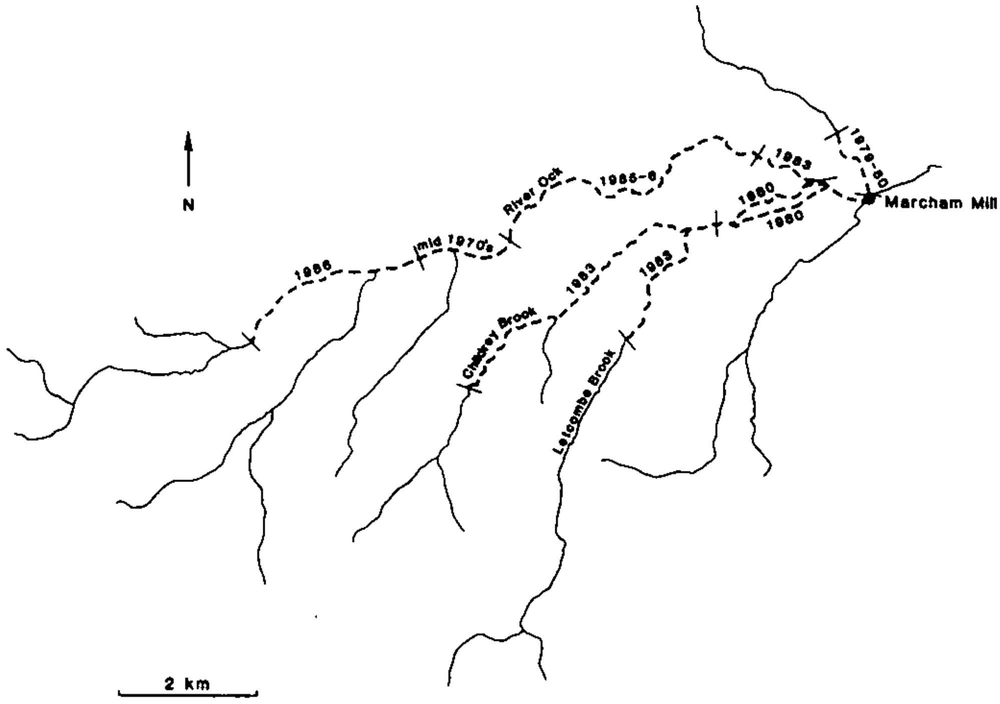



*Figure 6.7 Location and extent of channel improvements in the river Ock catchment*

catchment generally given over to dairy and livestock farming with some urban and industrial development near the catchment outlet. Flow records commenced in 1962 with a velocity area station at Ewenny Priory. The station was rated by current meter up to bankfull flows (about 20 $m^3/s$) and high flows are thought to be fairly reliable. The low flow records for the station were poor due to weed growth and to an unstable channel bed. Data processing ceased

*Table 6.5 Peak discharges for the river Ock. Data for 1987-9 are based on monthly maxima. The statistical significance levels are for differences between the first two periods*

| Period | Peaks > 8 $m^3/s$ mean | s. d. | num/yr | >10 $m^3/s$ num/yr | Annual max mean | s. d. |
|---|---|---|---|---|---|---|
| 1963-72 | 10.0 | 1.9 | 4.0 | 1.6 | 10.9 | 2.1 |
| 1979-86 | 10.6 | 2.3 | 4.1 | 1.7 | 12.4 | 2.4 |
| 1987-89 | 10.4 | 1.7 | - | - | 11.3 | 1.4 |
| Sig level | NS | - | NS | NS | NS | - |

in 1965 and the station was replaced by a flat v weir built some 500 m upstream in 1971 when a channel improvement scheme was being carried out. This flood protection scheme was intended to protect the new Waterton industrial estate, and the channel was enlarged to carry a 1:100 year return interval design flood of some 70 $m^3/s$. Further industrial development on the flood plain led to additional channel works and bridge enlargement in 1978. The effect of these schemes on peak flows can be seen from Table 6.6.

*Table 6.6 Peak discharges on the river Ewenny (statistical tests are for the last two periods)*

| Period | Peaks > 17 $m^3/s$ | | | >20 | Annual max | |
|---|---|---|---|---|---|---|
| | mean | s. d. | num/yr | num/yr | mean | s. d. |
| 1962-65 | - | - | - | - | 19.3 | - |
| 1971-77 | 21.0 | 4.0 | 2.4 | 1.5 | 24.4 | 5.1 |
| 1979-85 | 28.2 | 9.8 | 8.2 | 6.2 | 45.6 | 4.4 |
| Sig level | NS | - | .01 | .01 | .001 | - |

Between 1971-77 and 1979-85 peak flows (> 17 $m^3/s$) increased in average magnitude by 34% and in number by 340%. Annual flow maxima increased by 86%. As a direct consequence of the increased flood frequency downstream, a flood alleviation scheme had subsequently to be carried out in Ewenny village.

## 6.4.5 Low flows

It has often been stated that arterial channelisation works result in a reduction in low flows (Smailes, 1982; Wilcock, 1979). This is attributed to the fact that artificial drainage will result in greater drying of the soil between storms, so presumably reducing the amount of water available to drain under gravity to adjacent streams. On the other hand, it may be argued that just as it was shown in Chapter 4 that field drainage increased low flows so a similar effect would result from arterial drainage.

To resolve this, flow data from the four study catchments described above were analysed for evidence of changes in low flows that might correspond to the channelisation works. There are a number of ways of defining the low flow of a river (cf Ward and Robinson, 1990) in order to make comparisons between basins. These include the lowest flow ever recorded, the average annual daily minimum and the flow of a given exceedance (often that exceeded 95% of the time). The method used here is the mean annual minimum 7-day flow. A single day's flow is too short a duration, being liable to considerable bias by temporary artificial influences, whilst a week is a 'meaningful' period for many water resource purposes (Hindley, 1973).

Table 6.7 shows the mean annual 7-day flows for the four catchments, before and after the arterial drainage schemes were carried out. In all cases the low flows after drainage were higher than those before. This was statistically highly significant for both the Witham and the Ewenny using the Wilcoxon two-sample rank-sum test (Pearson and Hartley, 1972).

*Table 6.7 Comparison of mean annual 7-day flows ($m^3/s$) before and after arterial drainage. Standard deviations and periods are given in parentheses*

| River | Before | After | Sig level |
|---|---|---|---|
| Witham | .306 (.088)<br>(1960-66) | .480 (.078)<br>(1974-84) | .01 |
| Barlings | .046 (.025)<br>(1961-77) | .059 (.020)<br>(1980-86) | NS |
| Ock | .409 (.102)<br>(1963-72) | .450 (.021)<br>(1985-88) | NS |
| Ewenny | .312 (.053)<br>(1972-77) | .479 (.129)<br>(1979-88) | .01 |

The data appear to indicate that in these catchments arterial improvements coincided with an increase in low flows. This conclusion needs to be qualified, however. Firstly, there may be differences in the prevailing weather conditions between the periods before and after drainage (cf Arnell, 1989). Secondly, there may be artificial influences on the flows; thus for example since 1974 base flows of the river Witham have been augmented by water transfers from the Rutland Water reservoir.

Notwithstanding these caveats, it appears that just as with drainage at the field scale, arterial improvements result in an increase in low flows. This conclusion is made despite the frequent claims to the contrary. One reason for the popularly held opinion that arterial drainage reduces base flows is visual. Channel deepening means that the water surface is at a greater distance below the tops of the channel banks, whilst channel widening and weed clearance result in a shallower depth of flow. It may thus appear, to the casual observer, that after channelisation there is less water than in the former shallower, narrower and rougher channel.

## 6.5 INTERACTION WITH FIELD DRAINAGE OUTFLOWS

Arterial channels in agricultural areas should provide a free outfall for field drains discharging into them; to achieve this a 15 cm clearance is generally allowed between the invert of the field drain outfall and the water surface in the channel (Hockin, 1985).

Simulations using DRAINMOD were run for conditions in which the water level in the outfall ditch was held sufficiently high to prevent the field drains from discharging freely. These confirmed, not suprisingly, that gravity drainage of soil water was reduced and the soils were wetter than for conditions in which drainflow was not restricted. After all, ditch and arterial improvements are carried out to prevent such backing up occurring. Thus, when a field drainage scheme is carried out in France, the Agriculture Ministry requires that the capacity of the outfall ditches is limited, to throttle any excess flows from the drained land, by creating controlled and localised ponding of water. There is, however, little to stop the farmer removing the throttle at some later time! (G. Oberlin, CEMAGREF pers. comm.) At a specific site and time this effect would depend upon the relative water levels in the ditch and the water table in the field, and so would depend upon external factors affecting upstream inputs to the ditch, as well as downstream influences on its water level.

## 6.6 SUMMARY AND CONCLUSIONS

This chapter has presented the results of four catchment investigations in Britain, where arterial drainage schemes have altered the flood response, leading to increased flood flows and shorter response times. This change was especially large for the biggest events, which had been subject to the greatest amount of overbank storage and attenuation. Arterial improvements reduced local flooding, but may simply move the problem further downstream. This in fact happened at two of the study catchments where the channelisation works led to the need to build flood alleviation works at Lincoln and Ewenny.

Although the hydraulic effects of channel works are well established, their impact on flows is not incorporated in general flood estimation design (NERC, 1975). They may, of course, be calculated for a specific case by the use of river routing methods (cf Henderson, 1966) if sufficient channel data are available. The extent of overbank storage will be very dependent on the form of the floodplain; flood-prone reaches may be determined by ground survey and aerial photography (Blyth and Nash, 1980). Nevertheless, whilst it may be argued that every channelisation scheme will affect flows to a different extent, it was evident that in the, albeit small, sample examined here there was a close relationship between the design flood capacity of a scheme and the magnitude of its hydrological effects (Table 6.8). Larger channels will contain higher flood flows within them and are more likely to tap shallow aquifers and draw down the water table. Maps of the location of channel works are available for England and Wales (Brookes, 1981), whilst information on the design capacity of a scheme would have to be sought from the organisation responsible.

With the results of these studies of arterial drainage impacts on flows, and the effects of field drainage, attention can now be turned to consider the impacts of combined field and channel improvements. This is investigated in Chapter 7.

*Table 6.8 Design capacity of arterial channels (return period of flood) and their hydrological effects on maximum and minimum flows*

| River | Increase in flows after scheme | | Channel design capacity (years) |
|---|---|---|---|
| | Annual max. | 7 day min | |
| Ock | 14% | 10% | 10 |
| Barlings | 34% | 28% | 10 |
| Witham | 74% | 57% | 50 |
| Ewenny | 88% | 53% | 100 |

# 7. Catchment studies

## 7.1 INTRODUCTION

Although it is usually much more difficult than with small field studies to be certain that other factors are not influencing the results, there are a number of advantages to studying hydrological changes at the catchment scale :

(a) Flow records for rivers are more widely available and of much longer duration than measurements of flows from small-scale plots. The greater record lengths are important for the consideration of the response to extreme (high return interval) storm events which are unlikely to have been recorded by the generally short-term plot studies, and may exceed the discharge capacity of the field drains.

(b) It enables an assessment of the effect of drainage of just part of a catchment area. This may be expressed as a 'lumped' value, giving the proportion of the total catchment area affected, or expressed in a spatially 'distributed' way giving consideration to the location of the drained areas within a catchment.

(c) The effect of channel improvements and field drainage may be analysed together. This combination is more directly relevant to practical needs, namely that of understanding changes in the incidence of river flooding.

As Ward (1971) noted, although approaches such as plot studies and modelling are useful and valid, none of them is a replacement for catchment studies 'since ultimately all other methods must be verified and assessed in relation to watershed data'.

## 7.2 PREVIOUS CATCHMENT STUDIES

There has been a multitude of studies of the relation between changes in land use and catchment flows (Rodda 1976; Blackie *et al.*, 1980). These have often been concerned with the effect of planting or felling trees, rather than agricultural activities, and have tended to concentrate upon water yields rather than storm flood response.

Such studies have included a large number of differing techniques of data analysis. The simplest group of methods are confined to examining changes in the flow records alone (e.g. Woodward and Nagler, 1929; McCubbin, 1938). These are of limited value due to the natural variability of climate, especially flood producing events. Even where the flood records are related to records of daily precipitation (e.g. Howe *et al.*, 1967; Green, 1979; Brooke, 1983) the results may be inconclusive due to the difficulty of apportioning any observed change in flows between changed rainfall inputs or catchment storage and routing characteristics. Furthermore, long time series of daily precipitation records do not generally distinguish between liquid rain and snow. In Britain many large floods have been associated with snowmelt (Johnson, 1975) which will result in a mismatch between large falls and peak flows.

A more satisfactory way to determine whether the runoff response of a catchment has altered is by using a method which makes allowance for the storm rainfall characteristics. Two methods widely used are the 'paired catchment' and the 'experimental catchment' approaches. In the former, differences in storm characteristics and antecedent conditions are accounted for by comparison with flows from a 'control' catchment. This method enables direct comparisons to be made, but suffers from the disadvantage that no two catchments are identical in all other respects (soils, slopes etc.). The experimental catchment approach, whereby the rainfall-runoff response of a catchment is studied under changing conditions, requires a long period of record, but is the more appropriate technique for large river catchments, since a partial change in land use over a period of time is generally what happens in practice. This methodology was adopted in the detailed studies described in Section 7.3.

The following is a brief summary of some of the published catchment scale studies which are of most relevance to this investigation of artificial drainage effects.

Perhaps the earliest study in Britain was by Lewis (1957) of the Alwen and Brenig catchments in north Wales. Although principally concerned with the water yield from upland catchments he noted that forestry drainage operations resulted in a more flashy runoff response, but gave no further details.

Conway and Millar (1960) directly compared flows from adjacent drained (moorland gripped) and undrained upland catchments and found a much higher flood response from the drained catchments. Their results, and further data subsequently collected from the catchments, were examined by Robinson (1985) who confirmed their main conclusions regarding peak flows and corrected a later, widely quoted, misrepresentation that the drainage had reduced low flows (cf McDonald, 1973). The Moor House data were in fact inconclusive on this point.

Green (1973) opined that 'Underdrainage leads to increased rate of response of runoff to rainfall into the watercourses'. Some years later, however, he was less sanguine, having studied the Harpers Brook and Bury Brook catchments in eastern England, and found increases of a similar magnitude in the incidence of both peak flows and of heavy rainfall : 'More work needs to be done to determine what proportions of the noted effects can be attributed to field underdrainage and to the incidence of rainfall' (Green, 1979).

Robinson (1986b) studied the hydrological effect of the pre-planting forestry drainage of the complete headwaters of a small upland catchment. He reported that the drainage reduced the response time of the catchment from 2.1 to 1.6 hours and increased flood peaks by about 20%.

Warmerdam (1982) investigated the effects of agricultural drainage in the 6.5 $km^2$ Hupselse Beek catchment in the Netherlands. He fitted a lumped conceptual model to the pre-drainage rainfall and flow records, and concluded that drainage reduced peak storm flows. Baseflows were increased.

Following claims of increased river flooding in mid-Wales, the Severn Trent Water Authority examined rainfall and runoff records for two catchments, the Dulas at

Rhos y Pentref (52.7 km$^2$) and the Severn at Caersws (375 km$^2$). A comparison of unit hydrographs derived from storms in 1973-5 with those from storms in 1979-81 indicated 'a tendency towards more flashy floods at Caersws and to a lesser extent on the Dulas' (STWA, 1982). It was concluded that if the apparent tendency was real then it must have resulted from a widespread change in the catchments. Since the land is predominantly upland and used for grazing, it was suggested that changes in agricultural practices, involving grassland improvement, might be the cause. It was emphasised that the apparent trend did not prove anything, and that to confirm the trend would require many more events to be examined and be very time-consuming.

This task was taken up by Higgs (Higgs, 1987; Higgs and Petts, 1988) who examined additional storm events (as far back as the mid-1960s) and extended the study to nearby catchments. He concluded that the unit hydrograph peaks at Caersws had doubled, and attributed this to land drainage and pasture improvement, but could find no consistent trend over time for the other catchments. Unfortunately the value of the study is undermined by the fact that Higgs derived one-hour unit hydrographs (Higgs, 1987 p143) for the early period of record and compared them directly with half-hour unit hydrographs derived from more recent storms by the STWA (1982, p3). This difference in time interval would itself result in peakier unit hydrographs from the later data for Caersws. Data for the Dulas, in contrast, were taken from years in-between those studied by the STWA, whilst for the other catchments there were no comparable analyses in STWA (1982).

## 7.3 ANALYSES OF CATCHMENT DATA

Two rural catchments were selected for detailed study of the effect of field drainage on river flows : the Catchwater in Humberside (operated by the Geography Department of Hull University) and the Ray in Buckinghamshire (operated by the Institute of Hydrology). Both catchments have hydrometric data, including rainfall and flows, dating back to the 1960s. They are in areas which have experienced a rapid expansion of field drainage over this period and have contrasting soils types. The Ray catchment has heavy clay soils and contains Grendon field drainage experiments whilst the Catchwater has more permeable loam soils and contains the Withernwick field site.

A fundamental limitation of many previous studies of flow changes is that they lacked quantitative data on the extent of the land use change they aimed to study. For this investigation field by field records of drainage (areas and dates) were obtained from the master plans held at the local MAFF offices. At the time these data were abstracted from the records most of the individual files for the drainage schemes still existed, and it was possible to calculate not just the total amount of drainage but also the variation in drainage activity over time (Fig 7.1). This is, unfortunately, no longer the case.

Hydrometric data from both catchments have been processed and quality controlled using computer programs developed by the Institute of Hydrology (Plinston and Hill, 1974; Roberts, 1981). The main characteristics of the catchments are given in Table 7.1.

*Table 7.1 Summary of the characteristics of the study catchments*

| Name | Area ($km^2$) | Mainstream slope (m/km) | Soil type | Principal land use | Drainage (1940-80) |
|---|---|---|---|---|---|
| Ray | 18.6 | 4.82 | Clay | Grass | 45% |
| Catchwater | 16.1 | 1.29 | Loam | Arable | 25% |

Soon after the establishment of the catchments in the 1960s a land use survey was carried out in each. In both cases due to the large amount of work involved this has not been updated and any subsequent changes have not been recorded. This absence of more recent surveys is an important gap in the catchment information, since it is necessary in the study of flow records to be aware of the extent of any change in land use accompanying the increase in field drainage. To circumvent this problem, information was abstracted from the annual census returns on land holdings collected by the Ministry of Agriculture (HMSO, 1979). These provide aggregated information for each civil parish. The boundaries of the parishes were then overlain on a map of each catchment and the proportion of the parish lying within the catchment was calculated. The overall catchment land use was then estimated as the areally weighted average of the individual parish information, corrected for mapped information on non-agricultural land uses (such as woodland). The Ray catchment is predominantly covered by three parishes and the Catchwater by two. Although not ideal, these data provide a valuable indication of changes in land use over time. Over the last 20 years the land use in the Ray catchment has remained largely unchanged (predominantly grassland), whilst the Catchwater has experienced a small (10%) increase in the area under arable at the expense of grassland (Table 7.2).

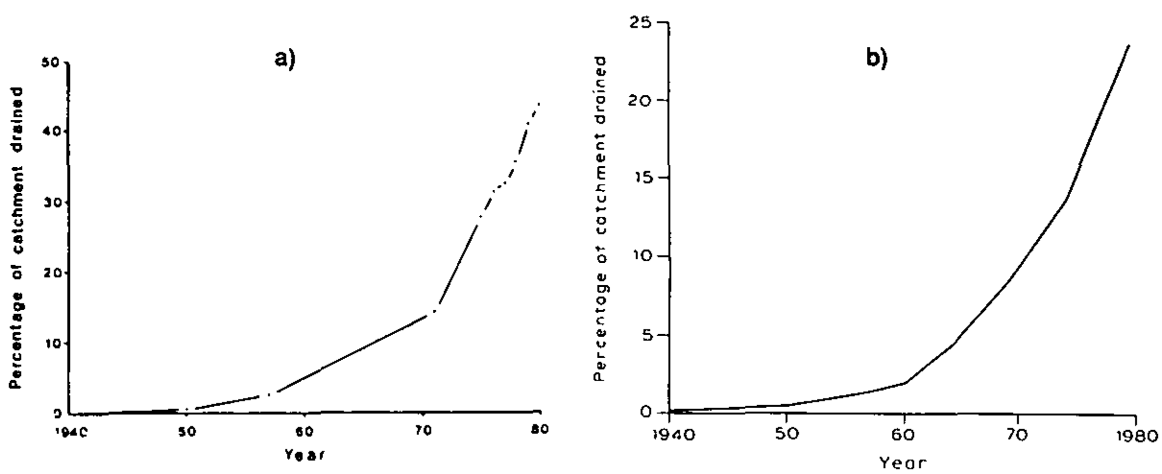



*Figure 7.1 Cumulative increase in field drainage, 1940-80, in the (a) Ray and (b) Catchwater catchments*

*Table 7.2 Land use in the Ray and Catchwater catchments (percentage of total area)*

| Catchment | Grassland Total | Grassland Permanent | Arable (excl leys) | Woods/other | Source |
|---|---|---|---|---|---|
| River Ray | | | | | |
| 1964 | 60 | ? | 20 | 20 | Field survey |
| 1978 | 58 | 49 | 22 | 20 | Parish data |
| 1985 | 58 | 48 | 22 | 20 | Parish data |
| Catchwater | | | | | |
| 1967 | 24 | ? | 75 | 1 | Field survey |
| 1978 | 28 | 18 | 72 | 1 | Parish data |
| 1986 | 15 | 13 | 84 | 1 | Parish data |

The apparent small increase in grassland in the Catchwater between 1967 and 1978 probably reflects the difference in the areas covered by the catchment survey and the parish boundaries. The field survey data did not distinguish between permanent grassland and temporary grass leys (part of the arable crop rotation). They are distinguished in the MAFF census data, and show that in the 1970s about 30% of the Ray and 80% of the Catchwater were used for arable cropping. The difference in land use between the catchments is a reflection of the land quality. Agricultural land in England and Wales has been graded according to the degree to which its physical characteristics impose long-term limitations on agricultural use (MAFF, 1977). These may affect the range of crops that can be grown, the level and consistency of yield, and the cost of production. The factors considered are climate, relief and soil; less permanent factors such as the standard of farm management (including artificial drainage) are not taken into account in the grading. Land in the Catchwater is predominantly Grade 3 (moderate limitations) with some Grade 2 (minor), whilst the Ray is mostly Grade 4 (severe limitations).

## 7.3.1 Changes in Ray flood response

The Ray catchment near Grendon Underwood in Buckinghamshire (Fig 7.2) is almost entirely used for agriculture, predominantly grass, with some areas of arable and woodland. The only industry is a brickworks. There is no significant urban development, and water supplies for the small village of Grendon are piped in from outside the catchment. Most of the domestic drainage is taken out of the catchment. The soils of the catchment were mapped in a special survey by Avery (1959). The majority are formed on virtually impervious clays (Jurassic clays or boulder clays). They have poor natural drainage and are waterlogged for a significant part of the year. The main soil series are Denchworth (a pelo stagnogley), Rowsham (cambic stagnogley) and Evesham (calcareous pelosol).

The catchment was instrumented for research purposes in 1963 by the Institute of Hydrology. Outflows are measured with a trapezoidal flume (Ackers and Harrison, 1963), rainfall data are available from a dense network of recording and storage gauges, and climate records are maintained.

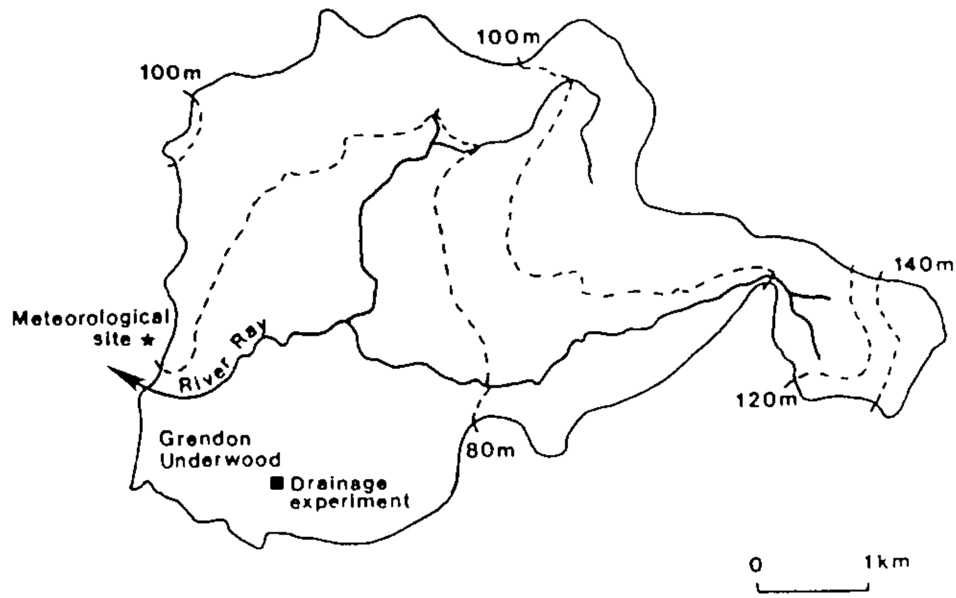



*Figure 7.2 River Ray research catchment*

The data have been used in a number of studies, and are considered to be relatively free from serious errors. The main elements of the water balance were discussed by Edwards and Rodda (1970) who concluded that the catchment is watertight. The long-term (1964-81) annual averages are given by Roberts (1989) as 635 mm precipitation (sd = 105 mm) and 175 mm discharge (sd = 70 mm). Daily hydrometric data were satisfactorily modelled by Eeles (1978) for the 12-year period, 1964-75. The short-term response of the catchment to storm events has been previously studied, using a 3-hour interval model for the four-year period November 1963 to November 1967 (Mandeville *et al.*, 1970). Subsequently, Beven (1980) looked at the 38 largest storms 1963-77 using hourly flow data, and found that 'peak discharge may be increasing slightly over time while the time to peak may be decreasing'. Neither variable was, however, statistically significantly correlated with time, and he pointed to the problem of distinguishing changes 'in the face of year to year variability of rainfall and other factors affecting antecedent conditions'.

In the light of these inconclusive results a detailed examination of storm rainfall runoff behaviour was undertaken in the present study using hourly rainfall and flow data. As a first stage, the pattern of peak flows over time is summarised in Table 7.3 and confirms the lack of a clear time trend.

Peak flows decreased in magnitude and frequency in the second period, 1969-73, and increased to former levels in the later periods. No periods were statistically different. Data for the storm events causing the 24 highest peak flows in the period 1963-77 were selected for detailed study. Later events were excluded due to a change in the recording rainfall network used to compute the areal catchment inputs. Events with multiple peaks or a snowmelt contribution were excluded from the study.

*Table 7.3 Peak discharges ($m^3/s$) for the river Ray*

| Period | Peaks > $1.9m^3/s$ mean | s. d. | num/yr | > 3.0 $m^3/s$ num/yr | Annual max mean | s. d. |
|---|---|---|---|---|---|---|
| 1964-68 | 4.33 | 3.03 | 4.8 | 3.2 | 7.05 | 4.74 |
| 1969-73 | 3.53 | 1.62 | 3.2 | 1.8 | 4.72 | 2.10 |
| 1974-78 | 4.22 | 2.05 | 5.0 | 3.0 | 6.40 | 0.81 |
| 1979-83 | 3.65 | 2.11 | 5.0 | 2.0 | 6.89 | 2.16 |

The events were analysed, using the same unit hydrograph approach adopted for the field plots (Chapter 4). To determine whether there had been any change over time, the events were chosen from the early and later part of the study period (Table 7.4). There were no statistically significant differences (using the Mann-Whitney rank test) in the storm rainfall, peak flow or storm runoff coefficients. The timing of storm runoff was also not significantly different, but the unit hydrograph was much peakier in the latter period (increase significant at the 0.05 level).

*Table 7.4 Comparison of storm runoff events for the Ray catchment*

| | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| 1963-68 | 0.89 | 22.5 | 5.4 | 54 | : | 4.8 | .096 | 14 |
| 1974-77 | 1.03 | 17.7 | 4.1 | 49 | : | 5.0 | .129 | 10 |

Parameters of the individual unit hydrographs are shown against time in Fig 7.3 and illustrate the change in the pattern of storm response over the period of study. Hydrographs were more peaky but response times were not significantly different.

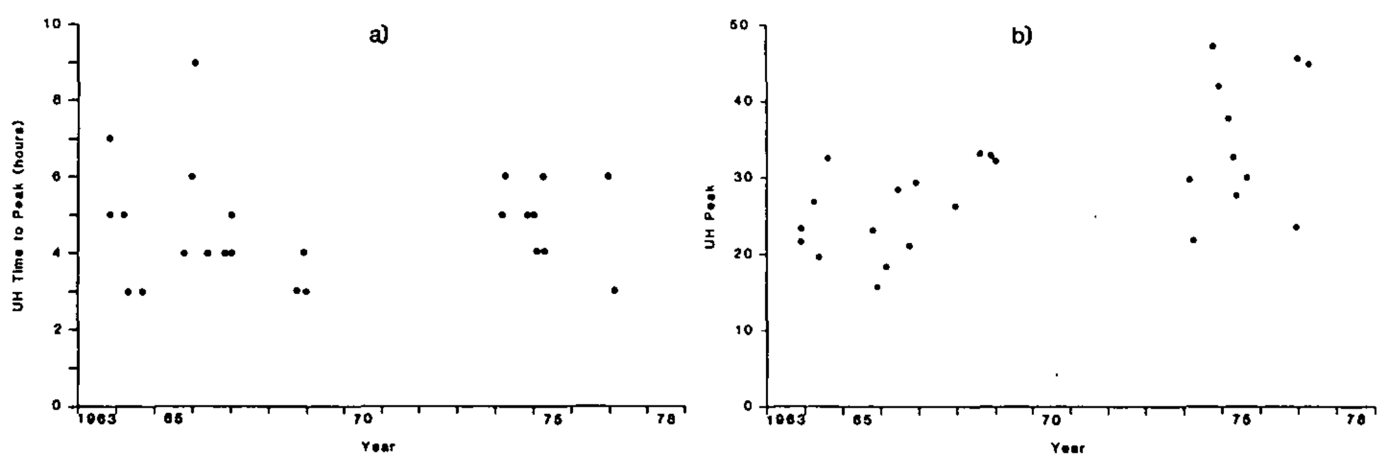



*Figure 7.3 Changes in one-hour unit hydrographs for the river Ray, showing a) time to peak and b) peak ordinate*

To illustrate these changes, average unit hydrographs, obtained using the superposition method (Boorman and Reed, 1981) are shown in Fig 7.4. This shows an increase of about 22% in the average (storm magnitude weighted) unit hydrograph peak.

These results suggest that there was an increase in peak storm response over the period 1963-77. A similar conclusion was reached independently by fitting a lumped conceptual rainfall-runoff model to hourly data from the early period of record, and comparing later observed storm responses against the simulated flows as a reference (Robinson *et al.*, 1990). In the absence of other activities in the catchment this change is felt most likely to be the result of artificial drainage. This increase is, however, in contrast to the smaller winter peak flows from the drained plot at the Grendon field drainage experiment situated in the catchment (Section 4.2.2). The reason for this apparent anomaly is discussed in Section 7.5.

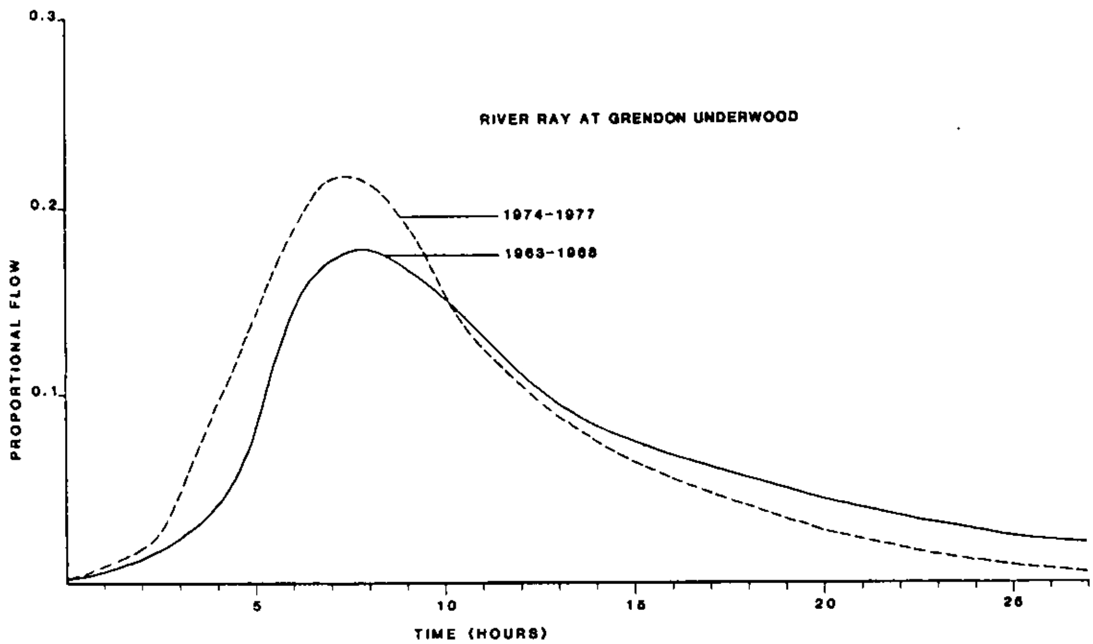



*Figure 7.4 Average one-hour unit hydrographs for the Ray showing the effect of field drainage on runoff response*

## 7.3.2 Changes in Catchwater flood response

The Catchwater Drain catchment lies about 15 km north east of Hull (Fig 7.5). It ranges in altitude between 10 and 20 m AOD and has low gradients. The catchment is almost entirely used for agriculture, predominantly arable farming with a rotation of grass and small grains (mainly wheat and barley). There is no industry and no significant urban development in the period of record.

The catchment was instrumented for teaching and research purposes by the University of Hull, and records have been kept since 1965 (Ward, 1967). Outflows are measured with a trapezoidal flume (Barsby, 1963) installed at a site where the channel is incised, preventing bypassing at high flows, and where there is a sufficient fall to prevent flows being influenced by backing up. Rainfall data are available from a dense network of recording and storage gauges, and climate records are collected (Ward, 1982).

The data have been used in a number of studies, and are considered to be free from serious errors. The main elements of the water balance have been discussed by Tang and Ward (1982) who concluded that the catchment is watertight. They gave long-term (1967-75) annual averages of 620 mm precipitation and 205 mm discharge. Subsequently, daily hydrometric data were used to develop and test a simulation model which gave a satisfactory fit to the measured flow data over a 13-year period (Ward, 1984; 1985).

The short-term response of the catchment to storm events had not been previously studied, so this was undertaken, using hourly flow and rainfall. Peak flows are summarised in Table 7.5, and show an apparent increase over time.

Peak flows reduced in frequency between the first two periods (statistically significant at .02 level for 0.7 $m^3/s$ threshold and .10 for 1.2 $m^3/s$). From the second period peaks then increased in the third and fourth periods (significant

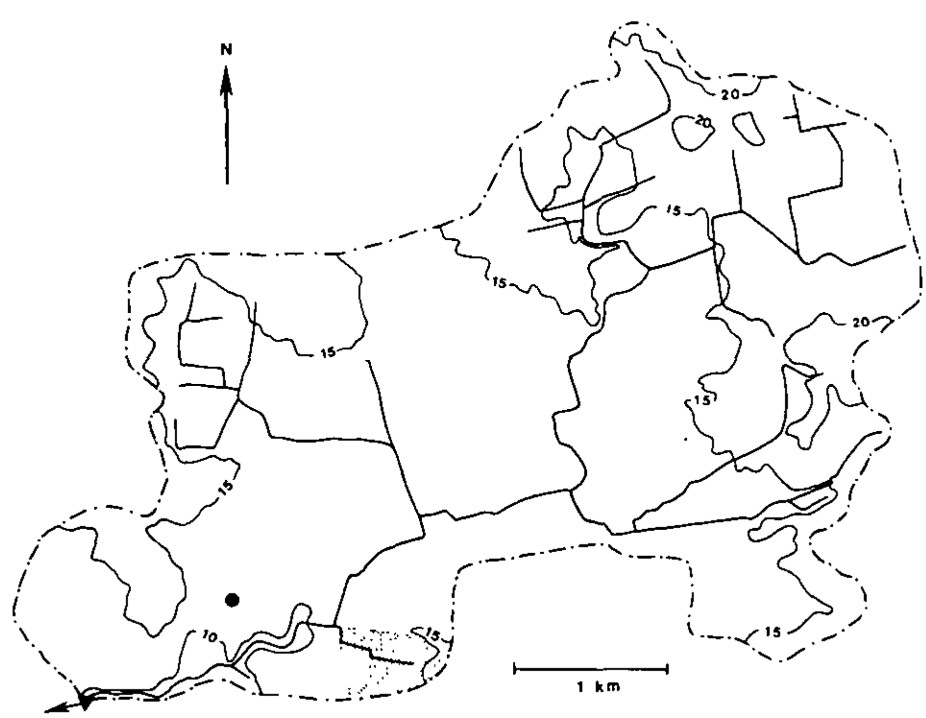



*Figure 7.5 Catchwater Drain research catchment*

at the .01 level), reaching frequencies that were higher than in 1966-69 (but not significantly so). The mean annual flood was over 25% higher at the end of the available period of record than in the first two periods (significant at .025 level).

*Table 7.5 Peak discharges ($m^3/s$) for the Catchwater*

| Period | Peaks > $0.7m^3/s$ mean | s. d. | num/yr | > $1.2\ m^3/s$ num/yr | Annual max mean | s. d. |
|---|---|---|---|---|---|---|
| 1966-69 | 1.19 | 0.29 | 7.7 | 4.5 | 1.60 | 0.21 |
| 1970-73 | 1.22 | 0.29 | 3.8 | 2.3 | 1.61 | 0.15 |
| 1974-77 | 1.31 | 0.62 | 6.3 | 3.0 | 2.19 | 1.15 |
| 1978-81 | 1.35 | 0.41 | 10.0 | 6.0 | 2.05 | 0.19 |

As with the Ray, the main time of high flows is from November to March, but the magnitude of flow peaks is only about one-third of that clay catchment (cf Table 7.3).

Data for the storm events causing the highest peak flows in the period 1971-9 were selected. Earlier events were excluded due to a problem of sediment accumulation in the tapping pipe of the flume, which was only resolved when the pipe was relocated. After 1979, site instrumentation was much reduced, and routine data processing ceased (Ward, 1982). Events with a snowmelt contribution or instrument malfunction were also excluded from the study. To avoid possible inhomogeneities in the rainfall, values from the climate station near the centre of the catchment were used.

Ten large events were analysed and parameters of the individual unit hydrographs are shown against time in Fig 7.6. They indicate a change in the pattern of storm response over the period of study. Hydrographs were more

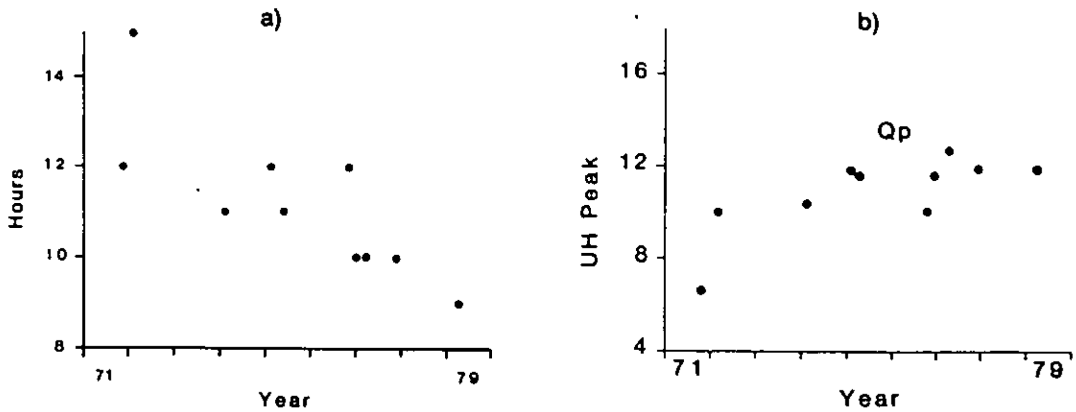



*Figure 7.6 Changes in one-hour unit hydrographs for the Catchwater showing a) time to peak, and b) peak ordinate.*

peaky and response times were shortened (both changes over time were significant at the 0.05 level). Average parameter values were determined for the first and second halves of the study period (Table 7.6). There were no statistically significant differences (using the Mann-Whitney rank test) between the two periods in the other storm parameters, namely observed rainfall, peak flow or storm runoff coefficients.

If the two sets of parameters are used as input to design flood estimation (IH, 1979), assuming the same runoff coefficient, these differences in timing would result on average in a 15% increase in peak streamflow. Applying the Flood Studies Report flood frequency growth curve for this area (NERC, 1975) indicates this increase is equivalent to the difference between a 5 and 10-year return interval flood. This is a sufficient increase to be of concern in some engineering schemes (Robinson, 1987).

*Table 7.6 Comparison of storm runoff events for the Catchwater catchment*

| | Qmax | Rtot | Rmax | %RO | : | Tp | Qp | N |
|---|---|---|---|---|---|---|---|---|
| 1971-5 | .077 | 19.1 | 3.2 | 50 | : | 12.4 | .037 | 5 |
| 1976-79 | .065 | 14.4 | 3.1 | 40 | : | 10.2 | .045 | 5 |

Average unit hydrographs, obtained using the method of Boorman and Reed (1981) are shown in Fig 7.7. The increase in the unit hydrograph peak was just over 20% - i.e. very similar in magnitude to that noted for the Ray catchment. In this case, however, the increase at the catchment scale was also reflected in an increase in peak flows at the plot experiment scale following its drainage (Section 4.2.4). This is discussed in Section 7.5.

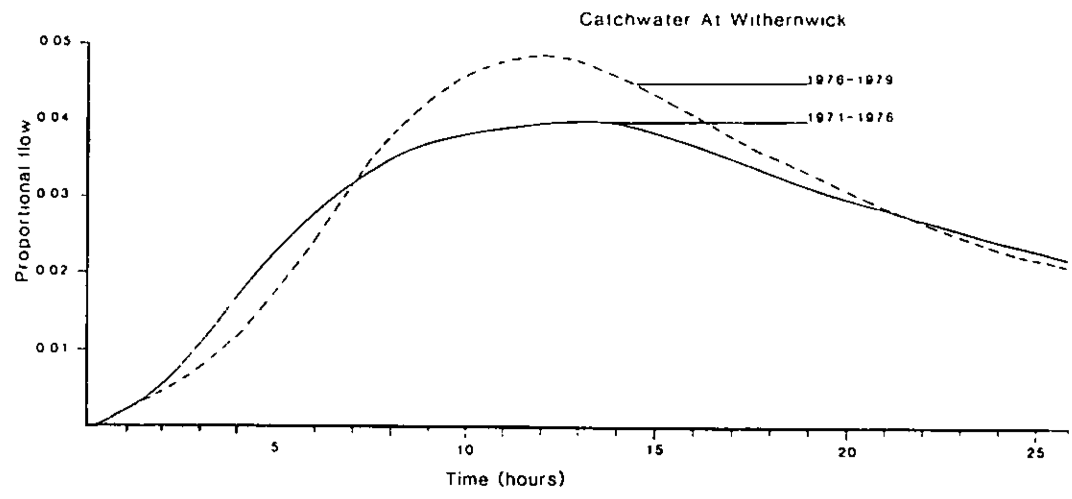



*Figure 7.7 Average one-hour unit hydrographs for the Catchwater showing the effect of field drainage on runoff response*

## 7.4 UPTAKE OF DRAINAGE WITHIN A CATCHMENT

Although as a consequence of the MAFF's policy of farmer 'confidentiality' individual fields receiving grant-aid for drainage may not be identified, the general location of drained areas in the Ray and Catchwater catchments may be shown (Figs 7.8 and 7.9). Unless there are strong physical constraints, drainage tends to be fairly randomly spread. Schemes usually comprise individual fields and it is exceptionally rare for a whole farm to be drained at the same time. The average size of drainage schemes in England and Wales is only 7 ha (Armstrong, 1978).

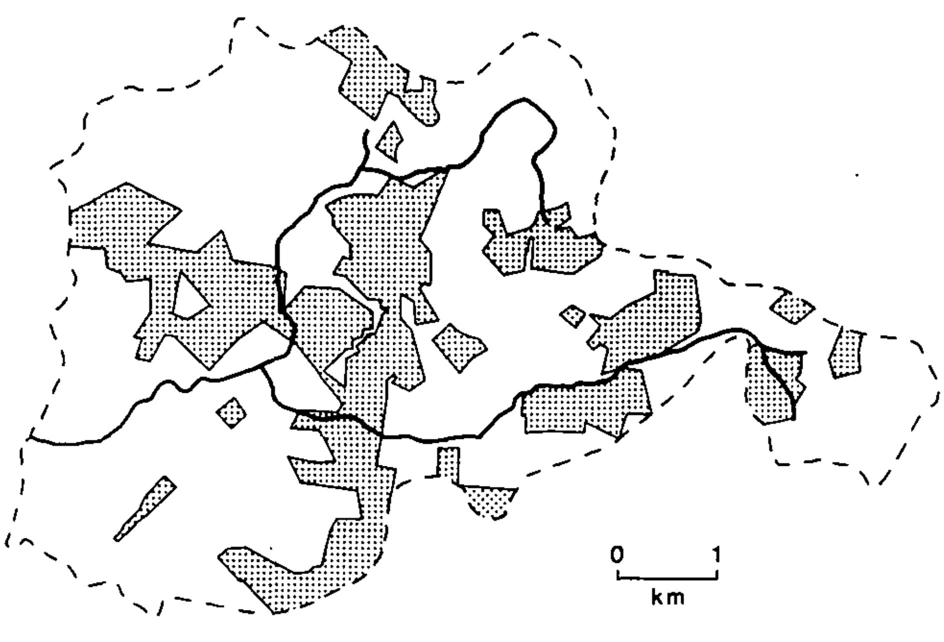



*Figure 7.8 Drainage in the Ray catchment, 1940-75*

Despite giving grant-aid for both in-field and arterial drainage, the MAFF do not have procedures to monitor the uptake of field drainage following arterial channel improvements (Miers, 1979). A special study was, however, undertaken for 16 schemes in the Severn Trent Water Authority area (Morris and Hess, 1986). These schemes ranged from 1 to 11 km of river improvements and were intended to benefit some 5,500 ha of land in total. It was found that farmland drainage could be only poorly predicted and was related to a number of factors. At the farm level, a change in management tended to encourage the uptake of drainage and, not suprisingly, the 'innovativeness' of the farmer (measured in terms of education, social participation and business motivation) affected the rate of farm drainage. At the field level, drainage was most rapid where it provided the greatest level of improvement. Proximity to farm buildings was also a significant factor, especially on dairy farms where the nearest fields are primarily used for milk cows. Typically about 6 years elapsed from the completion of an arterial channel scheme before 50% of the potential field drainage took place.

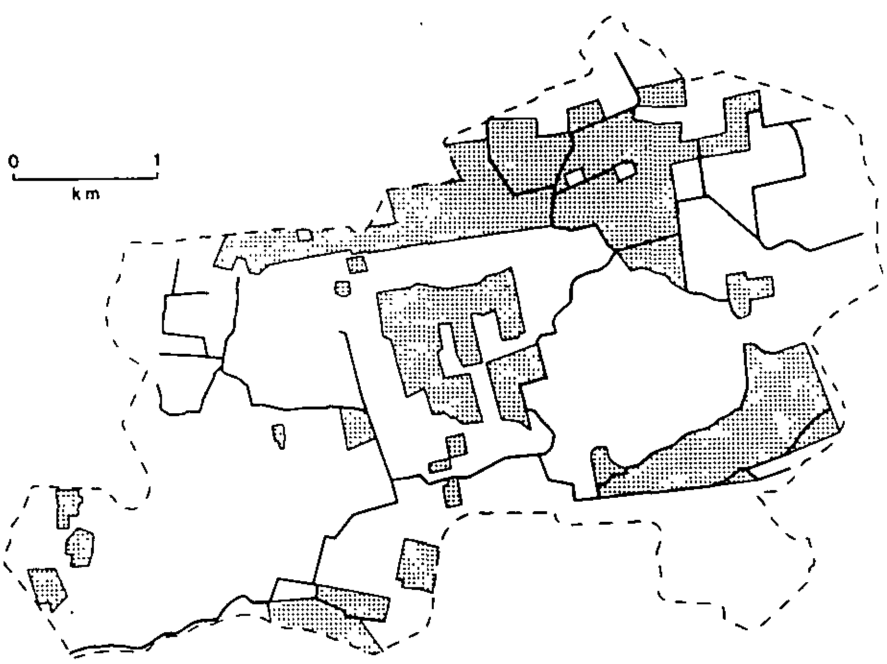



*Figure 7.9 Drainage in the Catchwater catchment, 1940-80*

In some cases, particularly for larger catchments in which the range of physical properties will be greater, there may be spatial differences in the location of drainage activity. This was evident in the national maps of field drainage (Chapter 2) and at the regional scale, for the counties of Berkshire, Buckinghamshire and Oxfordshire studied by Green (1975).

### 7.4.1 Rate of uptake

Differences in the physical characteristics of the land as well as differences between individual farmers mean that even when there is a clearly perceived benefit to be gained by installing drainage this will not necessarily happen in all areas at the same time.

This may be demonstrated most easily by an example where a physical constraint to field drainage has been removed. The Solway area of north west England is generally very flat and although the alluvial soils are potentially very productive they suffer from high water tables (Chapter 2). A number of arterial drainage schemes in the 1970s enabled farmers in areas near rivers that were previously subject to flooding to install field drains. Land that was formerly semi-derelict, used only for rough grazing in summer, could now be used to produce high quality grass for dairy production. In addition to enabling much heavier stocking rates, field drainage extended the grazing season, starting earlier in the spring and continuing later in the autumn. The take up of field drainage following the completion of eight such arterial drainage schemes is shown in Table 7.7 (based on data supplied by ADAS).

*Table 7.7 Take up of field drainage (percentage of the total area) in successive years since completion of the arterial drainage scheme*

| Scheme (river) | Date | Area (ha) | Cumulative area drained (%) 1 | 2 | 3 | 4 | 5 | 6 | 7 years |
|---|---|---|---|---|---|---|---|---|---|
| Trodder Syke | 1974 | 257 | 5 | 7 | 17 | 24 | 28 | 31 | 33 |
| Rumbling Br | 1974 | 105 | 15 | 15 | 17 | 22 | 32 | 32 | 59 |
| Andrews Sough | 1977 | 167 | 0 | 0 | 0 | 0 | | | |
| Rockerty Beck | 1975 | 94 | 0 | 0 | 0 | 2 | 15 | 23 | |
| Rook Beck | 1974 | 69 | 4 | 4 | 24 | 24 | 30 | | |
| Gamelsby Arch | 1977 | 24 | 0 | 0 | 83 | | | | |
| Cuddy Arch | 1975 | 210 | 8 | 11 | 33 | 45 | 52 | 54 | |
| Newton Holme | 1980 | 204 | 8 | 15 | | | | | |

The rate of uptake is expressed as a percentage of the potential 'benefit area'. This maximum area is calculated as the area of low lying ground which would benefit from field drainage. It excludes areas of 'automatic' benefit i.e. naturally free draining land (which would not require field drainage) or, more likely in this region, those parts of the catchment area which had already been drained and did not require further work in that respect. Data collection by ADAS ceased in 1980 or 1981, but it would be expected that in due course all of the benefit area would have field drains installed. The rate of uptake is quite variable between the eight schemes, and seems to take from 3 to over 7 years for half of the area to have field drains installed. Nevertheless, with the exception of the Andrews Sough scheme, the progress in field drainage uptake was considered by the local ADAS staff to have generally been satisfactory (S. Fenton, ADAS). The reason for the lack of drainage in that particular case is not known.

### 7.4.2 Effect of location

In both the Ray and Catchwater catchments the spatial distribution of field drainage was fairly random. It proved difficult to identify a well instrumented agricultural catchment in which drainage activity was confined to only one or two large subareas, in order to study the effect of drainage location.

In the absence of a suitable agricultural catchment it was decided instead to use the hydrometric records from the Llanbrynmair catchment in central Wales which was instrumented as part of a study of the effects of forestry on water quality (Leeks and Roberts, 1987). It comprises about 3 $km^2$ of peat moorland that was planned to be afforested. To promote tree establishment the catchment was progressively drained over a four-year period (using open plough ditches) until 70% of the area was affected (the remaining land was either too steep or was not planted). This period while the drainage was being carried out, and before the young sapling 'transplants' became established, provided the opportunity to study the effect on outflows of the drainage of different parts of a catchment (Fig 7.10).

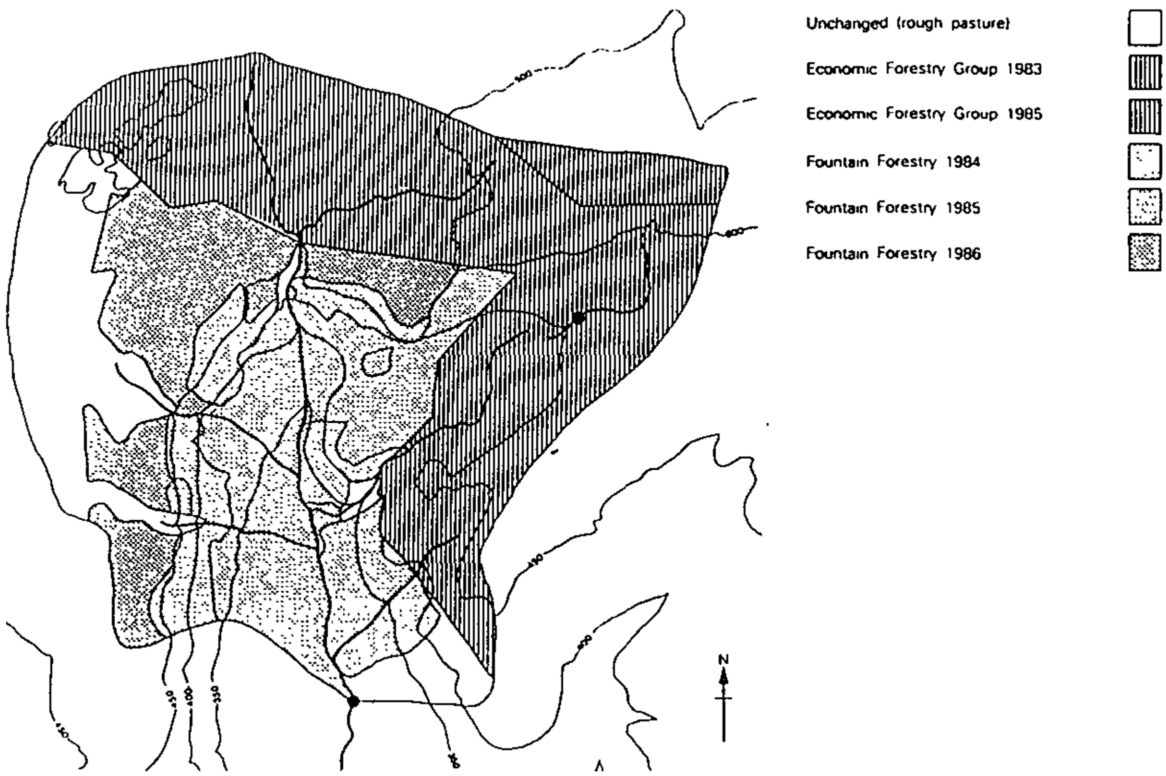



*Figure 7.10 Llanbrynmair research catchment, showing the pattern of drainage and the location of the subcatchment*

The catchment is equipped with a Crump weir at the outlet and recording raingauges. In addition, as part of a separate study of peat erosion (Francis, 1987), a V-notch weir with a chart recorder was installed on a tributary stream, measuring flows from a very small subcatchment (0.34 $km^2$) that was completely drained in one operation. This subcatchment was very useful since it enabled the impact of drainage upon flows to be determined at both the local and the catchment scales. The original chart records from the subcatchment were processed and analysed using the same procedures as with the field drainage studies. Comparison of unit hydrographs before and after the drainage of this subcatchment indicated similar hydrological effects to those at Blacklaw (Section 4.2.6), namely open drainage resulted in a much peakier storm flow response (Fig 7.11).

Drainage of the main catchment started on the higher ground most distant from the weir, and then moved to the valley bottom lands near to the catchment outlet. Drainage of the higher land (affecting 45% of the catchment area) gave rise to a much peakier runoff response recorded at the catchment outlet, but when the bottomlands (15% of catchment) were subsequently drained there was no further increase in peaks, although the response time of the catchment was shortened (Fig 7.12). This may represent the speeding up of flow from the areas near to the weir, building up the early part of the runoff hydrograph; any increase in the peak response was offset by the fact that this water was leaving the catchment before the arrival of waters from the more distant parts of the catchment. Subsequent drainage of a further 10% of the area, near to the centre of the catchment, produced no further increase in peaks - in fact maximum flows reduced somewhat, presumably as the ditches on the established areas became hydraulically less efficient. A similar reduction over time in peak flows has been noted following drainage of the Coalburn catchment in the Pennines (Robinson, 1986).

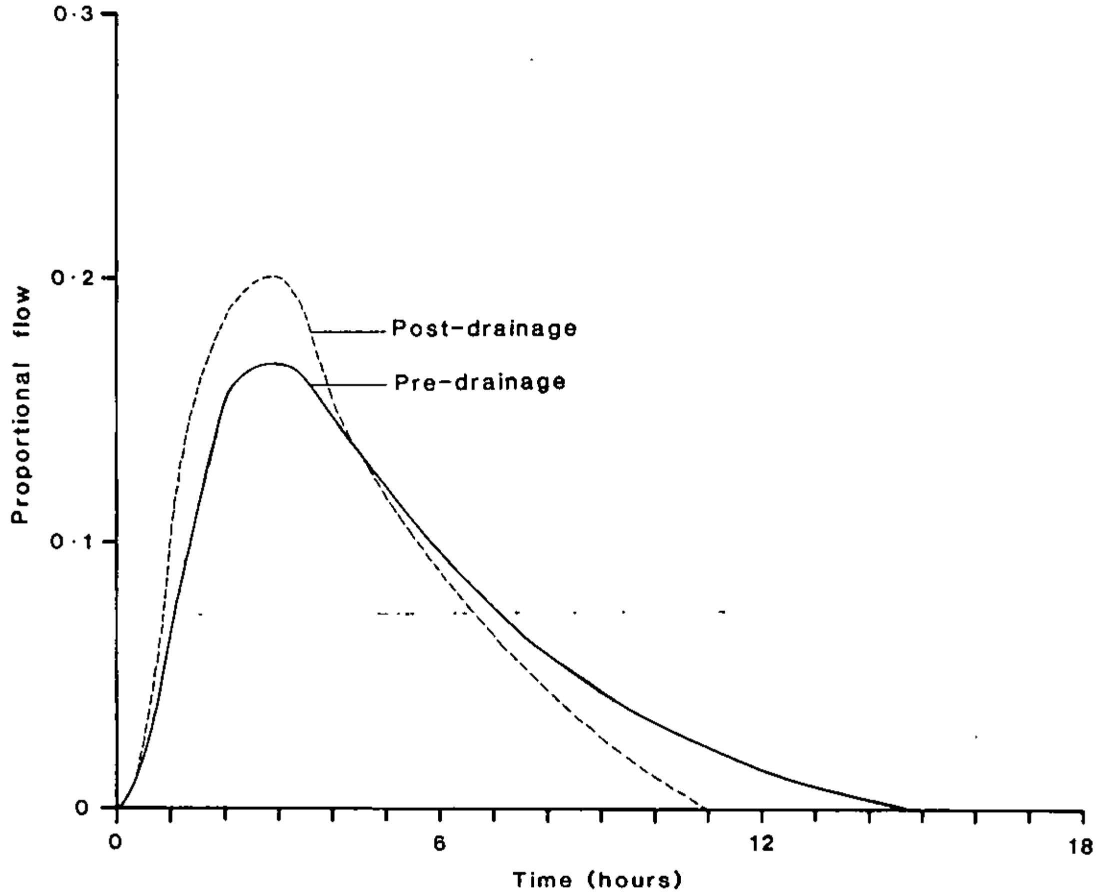



*Figure 7.11 Comparison of average one-hour unit hydrographs for storm events before and after drainage of the Llanbrynmair subcatchment*

The effect of the location of the drainage work in the Llanbrynmair catchment on its hydrograph may be contrasted with the results of a study of the Ettrick catchment in Scotland (Acreman, 1985). That catchment underwent extensive pre-planting forestry drainage with most early drainage near to its outlet and later drainage in the headwaters (i.e. the reverse to Llanbrynmair). The result was a small decrease in peak flows when the lower areas were drained, but as the drainage work extended further from the catchment outlet the peak flows were increased. Like Coalburn and Llanbrynmair this increase was reduced within a few years as the ditches became less effective.

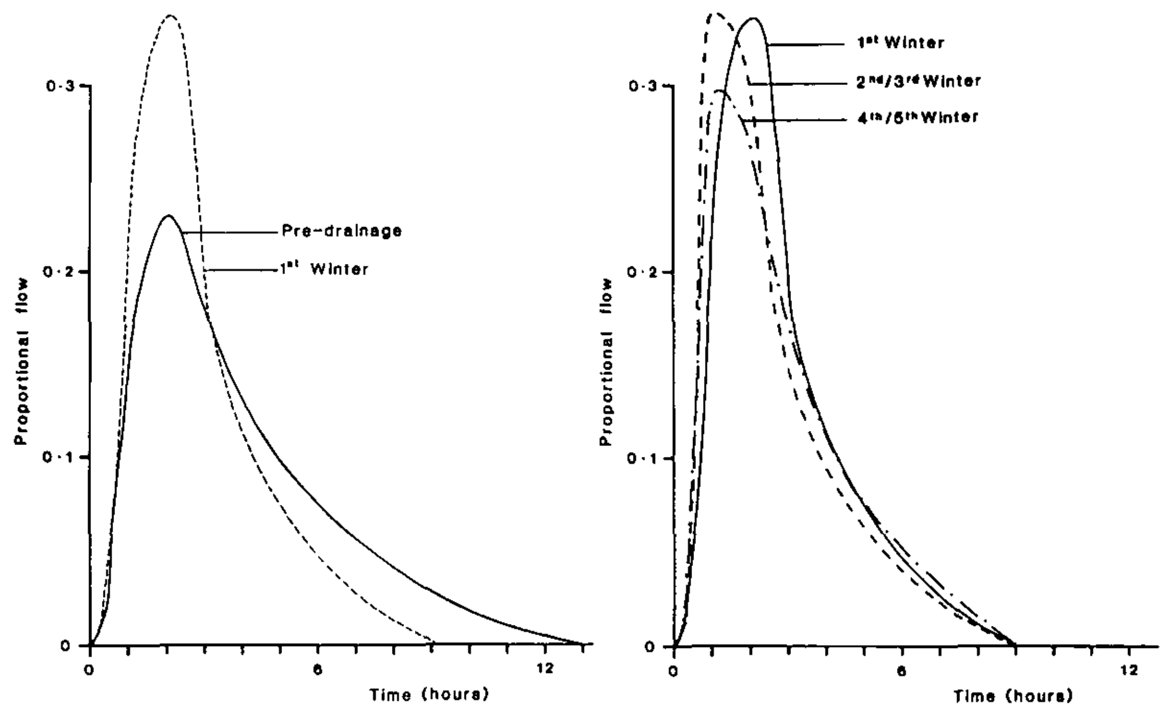



*Figure 7.12 Changes in the average one-hour unit hydrograph of the main Llanbrynmair catchment with the progress of drainage work (see text for details)*

## 7.5 SUMMARY AND CONCLUSIONS

The case studies in this chapter have shown that the impact of drainage may be different at the catchment and the field scales. The rainfall-runoff response increased over time from both the clay catchment (Ray) and the loam catchment (Catchwater), whilst at the field scale drainage reduced peaks from clay land and increased them from loam soils. This difference in effect with scale was not due to differences in the location of drainage within the two catchments, since in each case that was fairly uniformly distributed, but rather is the result of changes in the storage and lag effects of the stream networks due to 'improvement' works carried out. Information from the local water undertakings and from farmers confirmed that field ditches and the main channels had been improved in both catchments, alongside the uptake of field drainage. Whilst for the loam soil catchment, peak flows were increased both by the field scale drainage work and by the channel improvements, for the clay catchment the observed increase due to the channel works was partly counterbalanced by the reduced field scale peaks. Except for areas with contrasting physical characteristics, the spatial distribution of drainage in a catchment tends to be fairly random, being very dependent upon the motivation of individual landowners. In those catchments where drainage is uneven, the effect of the location of this work can be distinguished in changes in the catchment outflows. Thus, at the catchment scale peak flows may be increased by the speeding up of flows from distant parts of the catchment, or by attenuating flows from areas near to the outlet. Such distribution dependent effects may, however, be very difficult to predict since if drainage is localised, this may be due to differences in physical factors between those areas and the rest of the catchment. At Llanbrynmair, for example, only the less steep areas were drained; these areas would therefore have had a different pre-drainage response to the rest of the catchment.

The problem of scale is of fundamental importance in hydrology (Dooge, 1986). Different processes may be important as different sizes of catchment are considered. Thus, as larger catchments are considered, the importance of channel routing on the stream hydrograph will increase. Similarly, although Warmerdam (1982) reported a general reduction in peak outflows from the Hupselse Beek catchment following drainage of clay soils, he found evidence that in very big storms the peak flows were increased as the effect of the improved arterial network became dominant (Warmerdam, pers. comm.). In this chapter, the analysis was restricted to large events since they are of greatest practical relevance.

The impact of drainage upon catchment response depends upon a large number of site-specific factors which may be known only poorly, if at all. They include the natural response, and the number and location of field drains and arterial channel works. Given the fact that the limited available evidence indicates that at the catchment scale the combined effect of field and channel improvements is to increase peak flow response, it may be possible to propose a single catchment parameter to describe drainage development. The construction and application of this parameter in a national study of peak river flows is discussed in the next chapter.

# 8. Summary and conclusions

## 8.1 INTRODUCTION

The soil water regime of land can be radically altered by artificial drainage, and for many years there has been controversy about its impact on streamflow. Agricultural drainage has been carried out over extensive areas of the country for nearly two centuries. Estimates presented and discussed in this report suggest that some 5 Mha were pipe drained in England and Wales during the nineteenth century and a further 2 Mha in this century. Drainage became widespread during the period of 'High Farming' (about 1850-70) and was deemed to be the 'great improvement of the age' (Chambers and Mingay, 1966). This work was mainly concentrated in the wetter areas of the north and west. There was then a period of agricultural depression, which started about 1870 and only ended with the Second World War, during which time little drainage was carried out and many schemes fell into disrepair. Wartime exigencies and the strategic need to increase home grown food supplies led to government grant-aid payments and technical advice being given to farmers. It was recognised at that time that 'The lack of drainage still remains the chief impediment to increased productivity from much of our land' (Hill, 1942).

Agricultural prosperity and investment in drainage increased through the following decades and was particularly marked in the 1970s. An influential report to the Government by the Agricultural Advisory Council (Strutt, 1970) recommended 'A major campaign of drainage is needed if we are to achieve adequate drainage of agricultural land in the foreseeable future. This calls not only for a major investment on the part of the Government and the industry but also on a campaign to convince farmers that drainage is worthwhile'. It also recommended 'There must be a speeding up of the arterial works on which so much successful field drainage relies'.

The bulk of the drainage this century has been carried out on the better quality lands of the south and east so that, together with the drainage of many high rainfall areas in the north and west during the nineteenth century, most areas of England and Wales have experienced some drainage. In the more extreme environmental conditions, particularly those in northern and western Scotland, pipe drainage has never been an economic proposition; areas of underdrainage in both this and the last century being confined to the eastern and lowland areas. Even so, on low productivity hill land extensive attempts at drainage have been made by the cutting of open channels.

The pattern and extent of recent agricultural drainage are presented in Chapter 2 in an analysis of government records of field drainage schemes. These data identify both the most common types of drainage practices and those areas where drainage has been most extensive. They are typically productive clay soils lying in the lowland eastern parts of the country, and the use of secondary treatments to improve subsoil permeability is common. These data were previously unavailable at such a detailed scale and provide a unique picture of the areal extent of farm drainage based on over 100,000 schemes in

England and Wales and nearly 17,000 in Scotland. The collection of such records by government agricultural advisors has now ceased.

The boom in farm drainage in the 1970s ended in the early 1980s and current levels of drainage activity are low. Drainage in Britain has therefore gone through two 'cycles' of expansion and decay over the last 150 years. In both the peaks, in the nineteenth and twentieth centuries, the drainage activity was accompanied by claims and counter-claims concerning the effects that this work might have on river flow regimes downstream. As Nicholson (1953) noted, 'The connection between field drainage and flooding in rivers has been the subject of debate for centuries'.

## 8.2 THE DEBATE

The long-standing debate regarding the impact of drainage on river flows remained unresolved. This uncertainty was compounded by two factors. Firstly, there is a lack of observational measurements; even as recently as the mid-1980s Reid and Parkinson (1984) found that 'systematic analyses of land drainage hydrographs are rare'. As a consequence the debate has necessarily been theoretical, or used surrogate data for flows, specifically the water table lowering as a measure of flood runoff potential, to imply a likely effect of drainage. Secondly, due to the complex interactions of many factors (including the drainage system, soil properties and weather conditions) it is possible to argue almost anything. As Mark Twain remarked, regarding attempts to explain the vagaries of the flows of the Mississippi river, 'there is something wonderful about science, one can draw so many conclusions from such a few facts'. A review of the literature in Chapter 1 has shown that the arguments may be grouped into two 'schools of thought' :

(a) Drainage reduces downstream flooding. The purpose of drainage is to reduce soil saturation by lowering the water table. Thus when a storm does occur, the ground will be drier than similar, but undrained, land and so will be able to absorb more of the incoming rain - rather than it running off as surface layer flow. By changing the flow pathways from surface and near-surface flows to deeper flows to the pipe drains, the travel times will be increased. Thus it is argued that drainage will both moderate peak flows in times of storm rainfall and increase the response or lag times to peak flows. In addition, drainage will also tend to increase inter-storm baseflows by slow gravity drainage of soil water to the underdrainage systems.

(b) Drainage increases downstream flooding. The purpose of drainage is to reduce soil saturation by removing the soil water more quickly than it could get away naturally. By speeding up the rate of outflow from drained areas the peak storm flow will occur over a shorter period of time and inevitably maximum rates of flow will increase. In periods between storms the soil will be drier than in undrained areas and so dry weather flows are likely to be decreased.

These arguments have often been very 'partisan', with examples of apparent 'selectivity' of the data or of the references quoted. Discussing a similar debate about drainage in France, Oberlin (1981) felt that in addition to those cases where there had been a genuine effect on flows, claims about detrimental effects were made for a number of reasons :

- a lack of understanding of the ability of the pipes and channels to deliver water,

- the transfer of past, or present, opposition to a drainage scheme to its alleged or exaggerated effects,

- failure to recognise the natural year to year variability of climate, and consequently of river regimes.

The basic premise of this investigation is that only by the study and thorough analysis of real data can the conflicting theories and opinions be tested, and the debate finally be resolved.

## 8.3 SITE STUDIES

A central part of this study has involved assembling a nationwide set of data from both published and unpublished field experiments. A search was conducted for sites where rainfall, flows and soil water conditions had been recorded on both drained and undrained land. These sites were visited and assessed for suitability in this investigation and their data carefully scrutinised. Six sites were selected, four comprised 'before and after' drainage comparisons and two had adjacent 'paired' drained and undrained land. The raw data were obtained to ensure uniform quality control and data processing (Chapter 3).

The data from the selected experimental sites were analysed for evidence of differences in flow patterns between drained and undrained land. Unit hydrographs were derived, and compared between the drained and undrained condition at each site. At some sites drainage increased maximum flows, whilst at others drainage resulted in reduced peak flows. The findings at the different sites were then related to differences in site conditions. This included consideration of variables describing the topography, climate, soil properties and pre-drainage soil water regime, in addition to the type of artificial drainage system installed (Chapter 4 ). The results were compared with those in the literature as an independent check.

The work has shown a clear difference in drainage effect with soil water regime. In the data set of field experiments this difference was most closely related with soil type. It was found that, in contrast to previously expressed opinions (e.g. Trafford, 1973a) the drainage of heavy clay soils (prone to prolonged surface saturation in their undrained state) results in a lowering of downstream flow peaks. This is because their natural response is 'flashy' with limited available soil water storage, whereas when drained, surface saturation is largely eliminated. On more permeable soils, less prone to surface saturation, the usual effect of drainage is to improve the speed of subsurface flow, tending to increase peak flows. This finding is also at variance with earlier theoretical opinions (e.g. Rycroft and Massey, 1975; Bailey and Bree, 1981), which assumed that due to their higher porosity, drainage of these soils would always act to attenuate high flows.

A computer simulation model was used as a means to generalise the results of these empirical field studies (Chapter 5). The model used, DRAINMOD, simulates both surface and subsurface flows, and uses measurable soil and drainage system parameters. It may be run on long time series of weather data - in this study in excess of 10 years of hourly data were used for each of two field sites : Grendon and Withernwick. This enabled the effect of drainage on flows to be assessed over a wide range of conditions (both storm and ground state). DRAINMOD was first validated by application to the experimental sites, and results confirmed the key role of soil properties. The model successfully reproduced the difference in drainage effect between the clay soil at Grendon and the loam at Withernwick. The modelling work also shows the importance of rainfall regime - sites with higher rainfall regimes tend to show a reduction in peak flows with artificial drainage.

The results of the empirical studies and modelling exercise both emphasise the importance of the pre-drained response. At wetter sites (high rainfall and/or high clay content) peak flows are reduced, whilst at drier sites (lower rain, more permeable soils) peaks are increased. Guidelines are presented by which means the likely effect of artificial drainage (to worsen or reduce flood risk) at the field scale may be assessed from measurable site characteristics (Chapter 4). These parameters include the soil water regime and the physical properties of the soil profile.

### 8.3.1 Additional site factors

In addition to the presence or absence of artificial drainage, other local factors may be important for field outflows. Farming activities include a range of operations such as tillage and crop type and 'drainage can be considered to be just one more management factor; it is clear that drainage will interact with these factors making an evaluation of the effects of drainage alone very complicated' (Rycroft and Massey, 1973). The effect of farming practices is an extremely complex topic and although the subject of extensive research (particularly in N America) there is still much more to be understood before quantitative predictions can be made. There was no change in land use at the field drainage sites, so it was not possible to study the impact of such factors on flows, in addition to the direct drainage effect. Nevertheless some indications may be obtained from the literature of the hydrological consequences of these changes in farming. These include farm management practices and the type of drainage system.

***Land management***

Records of land use before and after drainage indicate that in the period 1970-81 there was an increase of 10% in the area under arable crops at the expense of grassland (Armstrong, 1981). A change from grass to arable cropping will be accompanied by an increase in ploughing. It has long been known that ploughing may reduce peak flows compared with unploughed land (e.g. Nicholson, 1943b; Lvovitch, 1980), and this finding has been confirmed in more recent studies (e.g. Parkinson *et al.*, 1988). The reduction appears to be the result of two factors. Firstly, tillage increases the macroporosity of the upper soil (Kuipers and van Ouwerkerk, 1963; Mackie-Dawson *et al.*, 1989) which increases infiltration and reduces the amount of surface runoff. Secondly, tracer studies have shown that ploughing disrupts the vertical continuity of pores between the upper soil and the soil layer below plough depth (Quisenbery and Phillips, 1976; Douglas *et al.*, 1980). This reduces the rate of downward flow to the subsoil (Goss *et al.*, 1978) and hence drainflow peaks, due to the increased travel times (Harris *et al.*, 1988). In Britain during the 1970s there was a move away from conventional ploughing of arable land to minimal cultivation and direct drilling. These are cheaper than ploughing as a much shallower depth of soil is disturbed, weeds being killed instead by use of herbicides. In theory, direct drilling involves no loosening of the soil as the seeds are inserted directly into the stubble of the previous crop, whilst in minimal cultivation the upper 5-10 cm are loosened. In practice the distinction is less clear since the need to incorporate the ash from stubble burning may require the turning of the surface 3 or 4 cm. Thus, in the major drainage and cultivation study conducted at Brimstone Farm direct drilling and minimal cultivation were used, but no distinction was made between them and both were called a 'direct drilling' treatment (G. Harris, pers. comm.). Perhaps not suprisingly the hydrological effects of such limited soil loosening have been found to be intermediate between those of ploughed land and undisturbed permanent pasture (Arrowsmith *et al.*, 1989). The effects of tillage and cultivation may vary between sites due to factors such as surface compaction by farm machinery, the formation of a plough pan or the sealing of the soil surface by raindrop impact at certain times of the year when arable farming leaves the surface bare. On sloping land the direction of ploughing (along the contour or the slope) may affect runoff considerably (Harrold and Edwards, 1972). Under minimal cultivation surface compaction of the soil may be a problem, particularly along wheel tracks (the so-called 'tram lines') and can result in substantial surface runoff (Lindstrom and Onstad, 1984); in heavy soils it may result in any existing cultivation pans being created nearer to the surface. Such management effects may be as important as drainage at the field scale on clay soils (Arrowsmith *et al.*, 1989) but they may be much less important at larger scales, being often local and temporary. They will vary from field to field and over time, with crop rotations as well as changes in farming practices. Minimal cultivation is much less widespread than drainage : only 4-5% of cereal land uses direct drilling (DOE, 1986). It has not gained the widespread adoption that was once anticipated due to problems of soil compaction and of grass weeds.

### *Type of drainage system*

The use of secondary treatment to improve rapid water movement has been found to result in 'peakier' hydrographs than a tile drain system alone (e.g. Trafford and Rycroft, 1973; Schuch, 1978). The importance of structural cracks for water movement in clay soils is now widely acknowledged. Leeds-Harrison *et al.* (1982) demonstrated experimentally the role of artificial cracks for water movement to mole drains. Galvin (1986) reported peakier hydrographs from mole drains with better developed cracks, and emphasised the importance of suitable soil conditions when moling is carried out to provide good shattering and crack formation. Seasonal variations in flows from mole drains were related to the shrink-swell properties of clay soils in plot experiments described by Robinson and Beven (1983) and Robinson *et al.* (1987).

The use of a permeable backfill in drain trenches is fairly common, particularly in low conductivity soils (Armstrong, 1981). It is designed to improve the connection between the tile drains and any secondary treatment, to permit a more ready entry of water to the drain and to act as a filter to prevent soil fines entering the pipe. Taylor *et al.* (1981) found that a permeable gravel backfill doubled the peak drainflow rates compared with those from drains which had been backfilled with soil a decade earlier.

There is also evidence to suggest that the effect of artificial drainage on flows will depend upon whether pipes or open ditches are used. As noted in Section 1.3.4, some authors have argued that pipes will give a less rapid response than ditches due to the extra lag time involved. In Britain, farm drainage is usually by subsurface pipes and it is only on upland peat soils where ditching is the primary means of soil water control. Two studies of peat drainage in Finland suggested that peak flows were lower from subsurface pipes than from ditch systems (Paivanen, 1976; Seuna and Kauppi, 1980). In the data set described in Chapters 3 and 4, the pipe drainage of peat at Staylittle reduced peak flows and the open ditching at Blacklaw increased peak flows, but the two sites differed in other respects too.

*Age of drainage system*

The effectiveness of any drainage system will decline with its increasing age. Pipe drains may continue to function adequately for perhaps 50 years, but secondary treatments (moling and subsoiling) to improve soil permeability have a much shorter life-span, of perhaps 5 years. A decline in peak flows with increasing age of secondary drainage has been noted in a number of studies (e.g. Childs, 1943; Robinson, 1987). The installation of the pipe drains in trenches, backfilled with soil or gravel, together with any secondary moling or subsoiling, will tend to increase porosity and hydraulic conductivity. However, if the work is carried out in unsuitable weather then compaction by the machinery will reduce the permeability and porosity. The long-term effects of the improved soil water regime can lead to changes in the hydraulic properties of the soil (Nemec, 1976; Bouma, 1986).

## 8.4 INDIVIDUAL CATCHMENT STUDIES

Whilst the effects of drainage at the field scale have been clearly demonstrated by the experimental studies and modelling, it is nevertheless true that any conclusions regarding the effects on river flows ultimately 'must be verified and assessed in relation to catchment data' (Ward, 1971). However, the observation of Found *et al.* (1974) is still relevant today : 'Although the theoretical relationships of drainage and other land use practices to the magnitude and timing of streamflow are widely referred to in the literature, very few quantitative studies have documented these impacts'. As a result, studies of the effect of drainage were made for a number of gauged river catchments (Chapters 6 and 7). Agricultural field drainage is often accompanied, or preceded, by improvements to the outfall channels. The effects of such improvements were studied for a number of catchments (Chapter 6). Arterial works increase flood peaks and shorten travel times downstream by reducing overbank storage and increasing channel velocities. The increase on flow peaks is greater for larger events (up to the capacity of the improved channel) since they were previously subject to larger overbank flooding and hydrograph tenuation. For a given inflow to an improved channel, the increase in the outflow peak will depend upon the capacity of the channel and the extent of the formerly flood prone area; a broad relation was found between the increase in the magnitude of the mean annual flood and the design flood return interval of the improved channel. Maps are available of the extent of improved channels in England and Wales, but unfortunately there is no source of readily available information on the flow capacity of individual schemes.

At the catchment scale any effect of drainage will be evident as a gradual change over time coincident with the cumulative uptake of drainage. It is necessary to use a rainfall-runoff model to separate the effect of climate fluctuations from anthropogenic effects (Refsgaard, 1987; Alley *et al.*, 1989). Here, this was achieved using the unit hydrograph technique, but alternatively a conceptual model could have been used (e.g. Robinson *et al.*, 1990). The long-term discharge and precipitation records of two rural catchments were analysed for evidence of changes in hydrograph response over time, given the known increase in the extent of agricultural drainage that has taken place in both basins. Each catchment contained one of the field drainage experiments that was described in Chapters 3 and 4, and successfully modelled in Chapter 5. Although the drainage effect differed between the two field sites - one showed an increase in peak flows, the other a reduction - when flows were examined at the catchment scale (about 17 $km^2$ ) in each case there was an increase in storm peak discharge. These results were interpreted in terms of a combination of the effects of both field drains and main channel improvements (Chapter 7).

The available data on the location of individual field drainage schemes, and the evidence from studies of farmer uptake, indicate that unless there are strong physical constraints the location of drainage will be fairly randomly distributed. In some areas, particularly in the uplands, drainage may be limited to particular areas and the effect of this concentration may be discernable on the catchment outflow; such effects would be very specific to an individual catchment and could vary between points on the stream network.

## 8.5 REGIONAL STUDIES

The preceding chapters dealt with the effect of agricultural drainage at the field scale (Chapters 3 - 5) and for individual river catchments (Chapters 6 - 7). This section investigates the effect of drainage on flows at the regional scale, and addresses the question whether drainage is important at the wider scale, or just for small-scale local situations. Notwithstanding the importance of site factors, such as soil type, drain type, land management, arterial works, floodplain form etc., it may be argued that for practical purposes the best general approach to producing quantitative regional estimates of the effect of field drainage on flows is by the use of a simple lumped parameter, to indicate the percentage of a catchment that has field drainage. For this study it was decided that the database of drainage in 1971-80, which was derived in Chapter 2, provided the most suitable source of information on recent drainage. This period represents half the drainage in this century, although it must be recognised that many nineteenth-century schemes may still be functioning to some extent. As an index of catchment drainage it also includes arterial works associated with the field drainage. There is a broad association between areas with field drainage and areas with improved main channels, although of course some field drainage schemes do not require arterial improvements, similarly in other areas with permeable soils, only arterial improvements may be required.

### 8.5.1 Catchment drained area

The topographic boundaries of many gauged river catchments in Britain have been digitised by the Institute of Hydrology to facilitate the estimation of catchment characteristics (including soil type and average rainfall) from maps for design flood estimation. Using the available software, these catchment boundaries were overlain on the gridded drainage data, produced in Chapter 2, to calculate the percentage of each catchment that had received drainage in the period 1971-80. Figure 8.1 shows the extent of this drainage in over 500 drainage basins in England and Wales. The majority of catchments have a modest distribution, but a few have a very extensive cover. Due to differences in the collection procedures in Scotland, it was reluctantly decided that for consistency between basins the calculation of catchment drainage should be restricted to England and Wales.

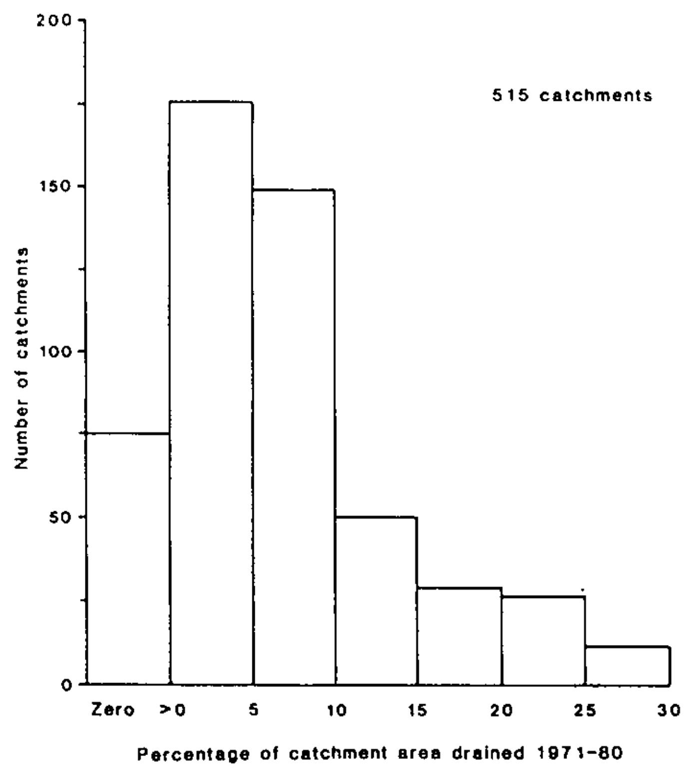



*Figure 8.1 Percentage drained land (1971-80) in a sample of catchments in England and Wales*

The estimated drainage in Ray catchment was 25% and that in the Catchwater was 21%. They are in the upper quartile of the drainage records, but are in no way exceptional. The accuracy of these estimates may be demonstrated by comparison with the field by field data (Chapter 7), which showed about 30% of the Ray and 16% of the Catchwater were drained over this period.

### 8.5.2 Regressions with catchment characteristics

As a first stage in the assessment of the role of drainage on regional flood flows the amount of drained land was correlated with catchment characteristics. This exercise used the national database of catchment characteristics compiled for the Flood Studies Report (NERC, 1975), which have been maintained and extended by the Institute of Hydrology. The selection and derivation of these parameters have been described in the Flood Studies Report (NERC, 1975 Vol I) and associated papers (Miller and Newson, 1975; Newson, 1975b). They will not be discussed in detail here, but the characteristics used in this study are briefly summarised. The catchment AREA is defined from topographic maps, SAAR is the long-term (1916-50) average annual precipitation and S1085 is the main stream slope, defined as the gradient between the 10 and 85 percentiles of the mainstream length (MSL). STMFRQ is a measure of stream density, measured as the number of channel junctions per square kilometre, and RSMD is an index of short-term flood producing rain (defined as the 5-year return period 1-day rainfall minus the average effective SMD). Soil properties (including wetness class, permeability and depth to an impermeable layer) were amalgamated into a single numerical index of likely hydrological behaviour, SOIL. To make some allowance for storage routing through lakes, a LAKE index was derived, being the proportion of the catchment that drains through a lake. For this study a new parameter 'DRAIN' was defined as the percentage of non-urban land in a catchment having field drainage in the years 1971-80.

The original data set used in the Flood Studies Report for correlations of catchment characteristics with storm unit hydrograph parameters comprised 130 catchments in total (of which 24 had >10% urban area). Following the collection of many additional event data and a substantial data quality checking excercise, Boorman (1985) presented slightly revised prediction equations. The unit hydrograph parameters and catchment characteristics used in this report are taken from the revised data set. A subset of the total number of available catchments was used in this study. Catchments in Scotland were excluded as their drainage data were not comparable with those for England and Wales. Those catchments with 5% or more urban development were also excluded since urbanisation can considerably alter the flood response of a catchment and the drainage data refer to the percentage of non-urban land, rather than of the total catchment area, and this avoids the possibility of 'double counting'. In addition, some new (post-FSR) catchments were excluded. These were mostly very small and steep catchments that had characteristics which lay well outside the range encountered in the Flood Studies Report (e.g. up to 150m/km main channel slope cf 118 maximum in the FSR). This provided a database of 111 catchments with catchment characteristics and drainage data. The ranges and mean values of these variables are given in Table 8.1.

*Table 8.1 Summary characteristics of the 111 catchments used in the regional study*

| PARAMETER | | MINIMUM | MEAN | MAXIMUM |
|---|---|---|---|---|
| Percent drained (1971-80) | DRAIN | 0.0 | 5.35 | 28.19 |
| Catchment area ($km^2$) | AREA | 1.5 | 133.5 | 510.0 |
| Mean annual rainfall (mm) | SAAR | 559. | 1207. | 3030. |
| Main channel slope (m/km) | S1085 | 0.92 | 11.88 | 63.70 |
| Stream frequency ($km^2$) | STMFRQ | 0.010 | 1.624 | 7.370 |
| Net 5-year rain (mm/day) | RSMD | 18.20 | 43.40 | 105.70 |
| Soil index | SOIL | 0.15 | 0.41 | 0.50 |
| Main channel length (km) | MSL | 0.10 | 21.59 | 70.65 |
| Lake index | LAKE | 0.0 | 0.016 | 0.260 |

Due to the wide range of parameter values logarithmic transforms were used in the Flood Studies Report to normalise the variables before multivariate analysis. Since both LAKE and DRAIN could have zero values a constant of unity was added. The correlation matrix between these variables is given in Table 8.2, and its structure may be compared with that in NERC (1975, Table II.4.8) for all the FSR catchments in Great Britain and Ireland. Attention here centres on the drainage parameter.

*Table 8.2 Correlation matrix of common logarithm transformed characteristics for 111 catchments in England and Wales*

| | DRAIN | AREA | SAAR | S1085 | STMFRQ |
|---|---|---|---|---|---|
| DRAIN | 1.0000 | | | | |
| AREA | 0.2119 | 1.0000 | | | |
| SAAR | -0.7671 | -0.1926 | 1.0000 | | |
| S1085 | -0.6882 | -0.6398 | 0.7231 | 1.0000 | |
| STMFRQ | -0.5141 | -0.1936 | 0.5624 | 0.5320 | 1.0000 |
| RSMD | -0.7683 | -0.2329 | 0.9682 | 0.7483 | 0.5500 |
| SOIL | -0.1875 | -0.2008 | 0.3178 | 0.3698 | 0.3953 |
| MSL | 0.0881 | 0.7092 | -0.0530 | -0.4037 | -0.1006 |
| LAKE | -0.1174 | 0.1881 | 0.1611 | 0.0102 | 0.1994 |
| | **RSMD** | **SOIL** | **MSL** | **LAKE** | |
| RSMD | 1.0000 | | | | |
| SOIL | 0.3506 | 1.0000 | | | |
| MSL | -0.0736 | -0.1844 | 1.0000 | | |
| LAKE | 0.1666 | 0.0911 | 0.1316 | 1.0000 | |

Due to the large number of observations, correlations >0.165 are statistically significantly different to zero at the .05 probability level, whilst correlations >0.230 are significant at .01. Many of the catchment characteristics are strongly interrelated, and so their correlations with DRAIN may be by association with another parameter rather than a direct causal link. Thus in multiple regression, where several 'independent' variables are used to explain the variation in a 'dependent' variable, the strengths of the individual correlations are not constant and vary with the different combinations of dependent variables. The results of multiple regression between the other catchment characteristics and DRAIN are summarised below (Table 8.3).

*Table 8.3 Regression of percentage drained land on catchment characteristics*

Dependent variable : Log(DRAIN)
Number of observations : 111

*** REGRESSION COEFFICIENTS ***

| | ESTIMATE | Std Err | t stat |
|---|---|---|---|
| CONSTANT | 5.057 | 0.611 | 8.27 |
| Log(SAAR) | -1.170 | 0.237 | -4.93 |
| Log(S1085) | -0.515 | 0.130 | -3.98 |
| Log(AREA) | -0.1458 | 0.0723 | -2.02 |
| Log(SOIL) | 0.471 | 0.259 | 1.82 |

*** ANALYSIS OF VARIANCE ***

| | sum sqrs | mean sq |
|---|---|---|
| Explained variation | 14.470 | 3.61740 |
| Unexplained variation | 7.798 | 0.07356 |
| Total variation | 22.267 | 0.20243 |

Coefficient of determination : 0.6498

The prediction equation for the percentage of drained land (DRAIN) from catchment characteristics is :

$$11.4 \times 10^4 \ \ SAAR^{-1.17} \ S1085^{-0.515} \ AREA^{-0.1485} \ SOIL^{0.471} \qquad (8.1)$$

The coefficient of determination is 0.6498, indicating that this equation 'explains' 65% of the variation in the percentage drained figures. All the regression coefficients are significant at the .01 level (t test). The relationships between the percentage of drained land and the individual characteristics of the catchments are shown in Figures 8.2 - 8.5.

The negative relation between drainage activity and the average annual precipitation demonstrates the dominance of economic factors (the distribution of high value crops) over purely environmental considerations. Most drainage, is in eastern and southern England where the annual precipitation is less than 1,000 mm. Most of this drainage is on low-lying areas with gentle gradients. Drainage uptake is only poorly related to soil hydrology. It is greatest in areas of low permeability, and is infrequent on both the least permeable soils (not economic) or the most permeable (not necessary). The negative relation between the percentage of drained land and the size of catchment considered is not suprising, since increasing scale will inevitably increase the range of conditions within a catchment. It indicates that for catchment areas over about 300 km$^2$ the extent of drainage (1971-80) is unlikely to exceed 5%.

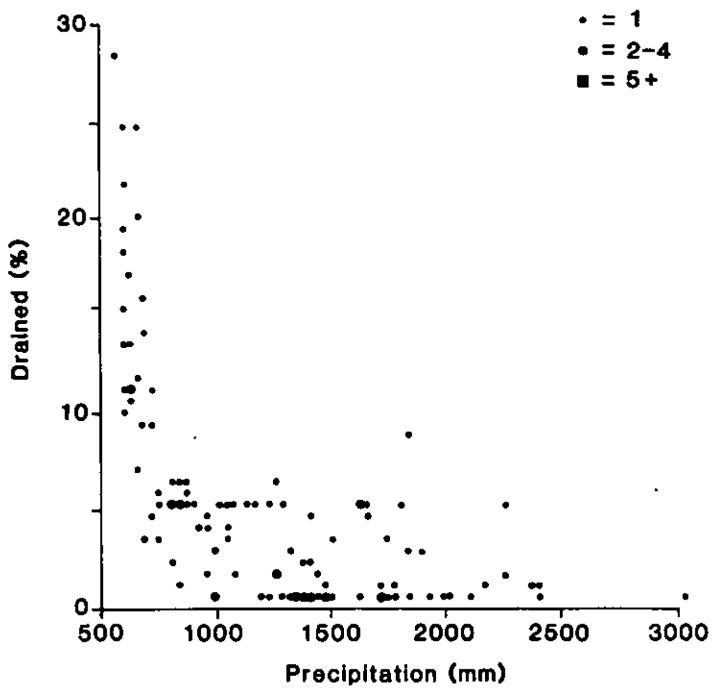



*Figure 8.2 Relation between the percentage of drained land and annual average precipitation*

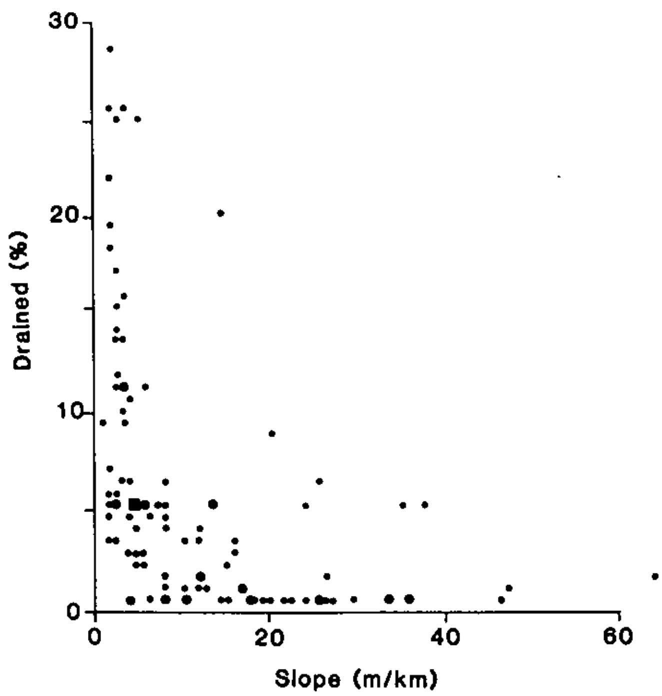



*Figure 8.3 Relation between the percentage of drained land and catchment slope*

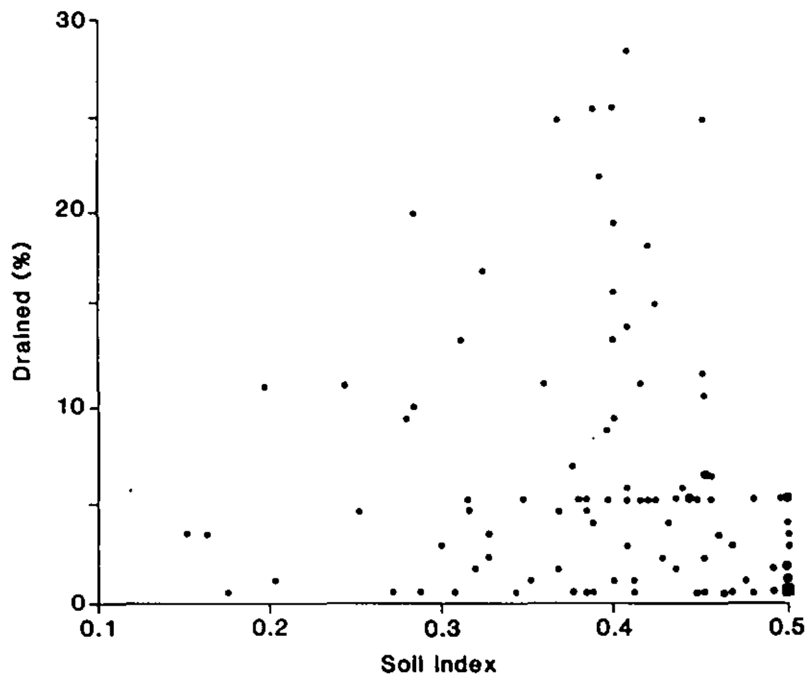



*Figure 8.4 Relation between the percentage of drained land and soil type*

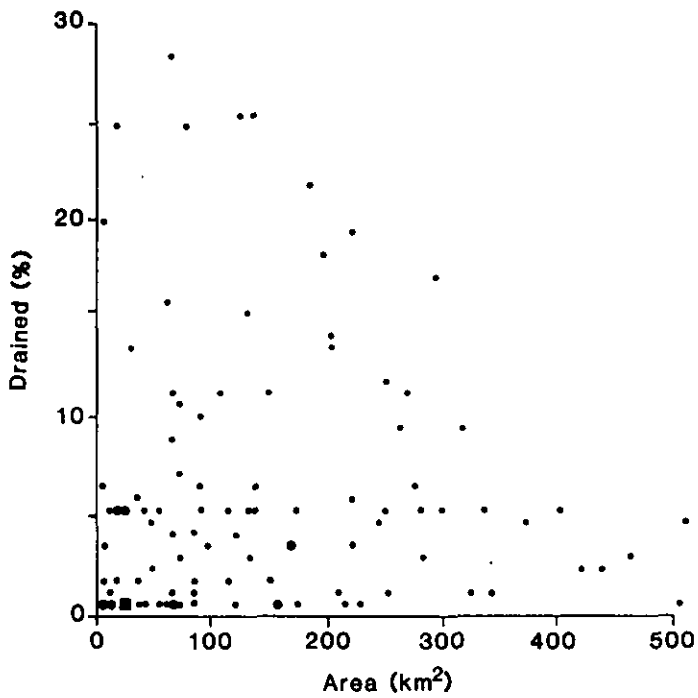



*Figure 8.5 Relation between the percentage of drained land and catchment size*

### 8.5.3 Regressions with flow parameters

The Flood Studies Report defined the shape of the one-hour unit hydrograph by fitting a triangle which had three parameters - time to peak, peak flow and width at half peak (NERC, 1975 Vol I Chap 6). The fitting procedure, and the need to ensure unit volume, ensured a strong interdependence between these parameters, and it was found that the shape could be described satisfactorily in terms of only one parameter. Largely on the basis of tradition, the average time to peak (Tp) was chosen as the key parameter. The annual maximum flood series were used in the FSR to define a best estimate of the mean annual flood 'BESMAF', based on observed flows together with record extention by correlation with nearby catchments. It would be inappropriate to use the BESMAF flood data with drainage in the period 1970-81, since they were derived from flow records prior to 1970. The collection of further flood data since that time enables the mean annual flood to be updated to 1986 (IH, 1988), and for this study a new variable, here termed 'NEWMAF', was created for catchments with 5 or more years of flow data. Mean and range values of these flow parameters that were available for the catchments in this study are given in Table 8.4.

*Table 8.4 Flow parameters used in the regressions*

| Parameter | | Minimum | Mean | Maximum | Number |
|---|---|---|---|---|---|
| Time to peak (hours) | Tp | 1.54 | 8.7 | 26.9 | 78 |
| Mean annual flood ($m^3/s$) | NEWMAF | 1.35 | 59.9 | 374.8 | 88 |

The correlation coefficients between these flow parameters and catchment characteristics are shown in Table 8.5. The .05 and .01 significance levels were 0.189 and 0.267 respectively for Tp, and 0.178 and 0.247 respectively for NEWMAF.

*Table 8.5 Correlation matrix of common logarithm transformed catchment and flow parameters*

| | DRAIN | AREA | SAAR | S1085 | STMFRQ |
|---|---|---|---|---|---|
| Tp | 0.5207 | 0.6052 | -0.7135 | -0.8811 | -0.4643 |
| NEWMAF | -0.3918 | 0.6289 | 0.5777 | 0.0943 | 0.3453 |
| | RSMD | SOIL | MSL | LAKE | |
| Tp | -0.7317 | -0.2997 | 0.3672 | -0.0164 | |
| NEWMAF | 0.5178 | 0.2557 | 0.4750 | 0.2470 | |

The simple correlation coefficents of DRAIN are significantly related to both flow parameters, and indicate drainage increases the time to peak and reduces the mean annual flood. This, however, makes no allowance for the interrelations with catchment characteristics described above : drainage is most widespread in drier, flatter catchments (two factors which act to reduce peak flows). The values of time to peak were then used as the dependent variable in a multiple regression with catchment characteristics. The result is summarised in Table 8.6.

*Table 8.6 Regression of one-hour unit hydrograph time to peak on catchment characteristics*

Dependent variable : Log(Tp)
Number of observations : 78

*** REGRESSION COEFFICIENTS ***

| | ESTIMATE | Std Err | t stat |
|---|---|---|---|
| CONSTANT | 2.919 | 0.460 | 6.34 |
| Log(S1085) | -0.4273 | 0.0873 | -4.90 |
| Log(SAAR) | -0.589 | 0.167 | -3.52 |
| Log(AREA) | 0.0841 | 0.0435 | 1.93 |
| Log(DRAIN) | -0.0992 | 0.0555 | -1.79 |

*** ANALYSIS OF VARIANCE ***

| | sum sqrs | mean sq |
|---|---|---|
| Explained variation | 5.840 | 1.45998 |
| Unexplained variation | 1.373 | 0.01880 |
| Total variation | 7.213 | 0.09367 |

Coefficient of determination : 0.8096

The coefficient for DRAIN is significant at the .04 level, and the remaining exponents are all significant at the .01 level. The equation accounts for 81% of the variation in Tp.

The form of the equation is very similar to that of the Flood Studies Report (NERC, 1975) and Boorman (1985), incorporating terms for slope, rain (SAAR or RSMD) and catchment size (AREA or MSL), but with the addition of the drainage parameter :

$$Tp = 830\ S1085^{-0.427}\ SAAR^{-0.589}\ AREA^{-0.0841}\ DRAIN^{-0.0992} \qquad (8.2)$$

The exponent of -0.0992 for DRAIN implies that drainage of 10% of a catchment would reduce Tp by 21%, and that 30% drainage would lead to a 29% reduction. However, regression coefficients should not be used to estimate the effect on the dependent variable of changes in the values of independent variables, due to their interrelations. This is shown by the fact that the simple correlation between DRAIN and Tp was positive, but when other catchment characteristics were taken into account, the relationship became negative.

A similar multiple regression exercise was carried out using NEWMAF as the dependent variable (Table 8.7).

*Table 8.7 Regression of mean annual flood on catchment characteristics*

Dependent variable : Log(NEWMAF)
Number of observations : 88

*** REGRESSION COEFFICIENTS ***

| | ESTIMATE | Std Err | t stat |
|---|---|---|---|
| CONSTANT | -2.571 | 0.253 | -10.15 |
| Log(AREA) | 0.9554 | 0.0419 | 22.78 |
| Log(RSMD) | 1.654 | 0.132 | 12.55 |
| Log(SOIL)) | 1.152 | 0.2365 | 4.88 |
| Log(STMFRQ) | 0.2106 | 0.0567 | 3.71 |
| Log(LAKE) | -2.91 | 1.24 | -2.34 |

*** ANALYSIS OF VARIANCE ***

| | sum sqrs | mean sq |
|---|---|---|
| Explained variation | 24.105 | 4.82094 |
| Unexplained variation | 2.554 | 0.03115 |
| Total variation | 26.659 | 0.30642 |

Coefficient of determination : 0.9042

The resulting equation for NEWMAF in this data set is :

$$0.0027\ AREA^{0.955}\ RSMD^{1.654}\ SOIL^{1.152}\ STMFRQ^{0.211}\ LAKE^{-2.91} \quad (8.3)$$

This equation accounts for 90% of the variation in the mean annual flood. The coefficent of LAKE is significant at .02, and those of the other variables at .001. The form of the equation is similar to that in NERC (1975) for BESMAF.

DRAIN does not appear in the regression; the next variable to enter the multiple regression is S1085, but that was not included in the equation 8.3 since it failed to be significant at the .10 probability level. Thus, using NEWMAF as the best estimate of catchment flood frequency there is no evidence that drainage has a significant effect on regional peak flows.

It is possible that flooding may have altered over time in some catchments due to the increase in field drainage, particularly in the 1970s. To investigate this the ratio of NEWMAF : BESMAF was used in regressions (BESMAF was derived from flood data prior to 1970). There was no correlation with the percentage of land drained, indicating that those catchments where drainage had been particularly high did not show changes in flood frequency that differed from those where drainage activity had been low. Similarly, there was no correlation between this ratio and any of the catchment characteristics described earlier.

## 8.6 CONCLUSIONS OF THIS STUDY

The effects of agricultural drainage on flows have been investigated by means of field studies, catchment studies and computer modelling. In addition, the international literature has been reviewed with references to work in Britain, Ireland, France, Germany, Finland, Canada, the USA, and the Netherlands; the conclusions of this study should be applicable to more than just British conditions.

The findings of this study have shown that general statements to the effect that drainage 'causes' or 'reduces' flood risk downstream are over-simplifications of the complex processes involved. Consequently it might prove unwise to follow advice in the literature to reduce the design flood capacities of structures if the contributing area upstream has been artificially drained (Bailey *et al.*, 1980). The effect depends upon the particular circumstances. The impact of drainage upon flows can best be discussed by consideration at different scales, since that controls the mechanisms involved.

### 8.6.1 Field scale effects

At the field scale the effect of soil type is very important. This was recognised by earlier authors, using theoretical arguments, but they incorrectly argued the direction of change. Rather than reducing peak flows from permeable soils and increasing them from clay soils, the actual effect is shown to be the opposite. Drainage reduces peak flows from clay soils, and increases them from permeable soils (Robinson, 1985; 1987; 1989a,b) This view has now also been adopted by MAFF's specialist Field Drainage Experimental Unit (Arrowsmith *et al.*, 1989).

The type of drainage may also be important. Secondary treatment (moling and subsoiling) gives higher discharge peaks than pipe drains alone, and open ditches give higher peaks than subsurface drains.

Farming practices affecting soil compaction and tillage may have a significant effect on flows under local circumstances, but will vary widely from field to field as well as from year to year (and during the year) and are unlikely to be important for all except the smallest of catchments.

Drainage altered storm runoff timing, but did not significantly effect storm runoff volumes.

Baseflows were increased, rather than decreased, following drainage. Computer simulation modelling showed this was due to the greater depth of the drains providing a deeper outlet for gravity drainage of water from the soil profile. The increase in low flows occurs whether peak flows are increased or decreased.

The effect of drainage may vary at a site with the ground condition. Cracking clay soils may produce higher drainflow discharges than undrained land in summer, but lower peaks in winter. However, for all except the smallest catchments winter is the main flood season due to the greater volumes of flow. The maximum carrying capacity of the pipe drains will impose a limit on peak discharges, although surcharging will enable higher peak flows than the theoretical design, and the backing up of water in the drain trenches may result in higher site peak outflows due to the generation of saturation excess overland flow.

This investigation indicates that it may be possible to predict reasonably confidently the effect of drainage on the outflows from a given site by an examination of the site properties. This is based on a knowledge of the soil water regime of the undrained land (or, if unavailable, from the soil texture and the rainfall).

### 8.6.2 Catchment scale effects

The impact of drainage at the catchment scale may differ from that at the field scale due to the effect of the routing of flows from different parts of the catchment, and to the effects of improvements to the arterial channels and ditches. Ditch improvements will speed up flows and may cancel any effects of field drains reducing outflow peaks. Most drainage is on relatively flat land and requires good outfall channels.

Arterial channel improvements lead to increased flow peaks downstream due to the higher channel flow velocities and a reduction in overbank flooding and attenuation. This increase was greater for larger channels and for bigger flows.

It is often said that arterial channel improvements simply move the problem of flooding further downstream. Conversely, any reduction in channel maintenance by the NRA, farmers and local authorities will lead to an increase upstream in the areas of localised flooding.

Due to the lagging and routing of subcatchment flows to the outlet, increases in peaks at one point in a channel network may result in decreases at other points in the system. In Britain, field drainage is often very dispersed over a catchment. It is mostly very small scale, rather than in large blocks, and its uptake is greatly influenced by the attitudes of individual farmers.

Drainage altered flood timing but not volumes. Hewlett (1982) argued that due to the lagging and routing of subcatchment flows, what matters for peak flows at the main catchment outlet is whether a land use change has affected the subcatchment flood volumes rather than the peaks : 'it is not the peak discharge in the headwaters that produces the downstream flood, but rather the volume of stormflow released by the headwater areas'.

It has been claimed that in extreme rainfall events where the rainfall intensity exceeds the infiltration capacity of the ground the presence of field drainage will be unimportant (Oberlin, 1981). This is not necessarily true for the catchment scale since the improved ditch outfalls for the drains will facilitate the removal of overland flows.

Notwithstanding the views of many conservation scientists (Newbold, 1977) and fishermen (Morland, 1989) the available evidence indicates that artificial drainage increases baseflows, at both the field and river catchment scales.

The effect of drainage on the mean annual flood was not discernable in a regional study, although it was significantly related to catchment response time. It must be recognised that many other characteristics vary between catchments, and drainage is only one of a wide range of factors affecting catchment outflow patterns. This lack of a significant relation between drainage and flood frequency does not contradict the single-catchment studies in which the observed effects on flows of changing drainage activity over time were studied with constant values of the other catchment parameters (area, slope, soil type etc.).

There is some evidence that drainage may result in a slight increase in water yield due to a reduction in evaporation losses from the drier ground. This may, however, be balanced by an increase in water use by the healthier plants.

In very large storms, when the rainfall intensity is greater than the infiltration capacity of the soil or the flow capacity of the drains, the total flow peaks may be dominated by the greater density of open channels in drained land. It is also in larger events that the increase in peak flows due to arterial channel improvements was most pronounced.

This study has shown that there is a need to consider the land management history of a catchment when assessing its flows; even an apparently 'stable' catchment with little change in land use may show changes over time in the rainfall-runoff relationship.

It has also demonstrated the value of small 'process' studies. Without them, the river catchment data alone would not have shown the importance of soil type. Nor would it be possible to distinguish between the effects of field drains and arterial channel improvements.

## 8.7 THE FUTURE

It might be argued that the current decline in British agricultural activity would mean that any effects of drainage can be ignored as old drainage systems fall into decay and are not replaced. Such a view ignores the fact that as drainage systems fail, flows downstream may be affected, but in the opposite direction to that when the drainage was installed. This change will be particularly rapid where secondary treatment is not renewed.

The present situation could change, however. There have been rapid reversals in agricultural prosperity in the past. Following Britain's entry to the European Community in 1973 there was a 50% expansion in UK food production (Marks and Britton, 1989), encouraged by the system of high levels of agricultural price support. Agriculture was encouraged by the policy makers : 'The government take the view that a continuing expansion of food production in Britain will be in the national interest' (HMSO, 1975). Now, in order to reduce over-production, the UK is committed to reduce agricultural production by 20%, and the government provides grants to farmers who turn land over to fallow, non-agricultural uses or forestry (MAFF, 1988). Future changes in government policy could reverse the situation again.

# Acknowledgements and data sources

Field drainage data for England and Wales were obtained from MAFF (Guildford) and for Scotland from DAFS (Edinburgh).

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The DRAINMOD computer program was obtained from W. Skaggs and K. Konyha (University N. Carolina).

Hydrometric data and information on channel improvement schemes were provided by the National Rivers Authority (Anglian, Thames and Welsh Regions).

The gridded drainage data are held on a relational database (Oracle, 1985) at the Institute of Hydrology.

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# References


Ackers, P. and Harrison, A.J.M. 1963. Critical depth flumes for flow measurement in open channels. *Hydraulics Research Station Paper 5*, Wallingford.

AFT, 1973. County Leitrim resources survey: land use potential. *Soil Survey Bulletin 29.* An Foras Taluntais, Dublin.

Alexander, L. and Skaggs, R.W. 1987. Predicting unsaturated hydraulic conductivity from soil texture. *J. Irrigation and Drainage Engineering* 113: 184-97.

Al-Soufi, R. and Rycroft, D.W. 1973. A method for calculating the effects of mole drainage. *FDEU Technical Bulletin 75/2*, MAFF, London.

Alley, W.M., Refsgaard, J.C. and Vuglinsky, V.S. 1989. Joint application of trend testing and hydrological models in distinguishing between human influences and climatic effects on the hydrological cycle. Conference on climate and water. Publications of the Academy of Finland, Helsinki 413-25.

Anderson, J.L. and Bouma, J. 1973. Relationships between saturated hydraulic conductivity and morphometric data of an argillic horizon. *Proc. Soil Science Society of America* 37: 408-13.

Anon, 1967. Grendon - soil moisture sampling. *Subsurface Report 14*, Hydrological Research Unit, Wallingford.

Archer, D.R., 1989. Flood wave attenuation due to channel and flood storage and effects on flood frequency. In Beven, K. and Carling P., (eds) *Floods - Hydrological, Sedimentological and Geomorphological Implications*. J. Wiley, Chichester.

Armstrong, A.C. 1978. A digest of drainage statistics. *FDEU Technical Report 78/7*, MAFF, London.

Armstrong, A.C. 1980. The hydrology and water quality of a drained clay catchment - a preliminary report on the Cockle Park drainage experiment. *Report LDS/3*, MAFF, London.

Armstrong, A.C. 1981. Drainage statistics 1978-80. *FDEU Technical Report 80/1*, MAFF, London.

Armstrong, A.C. 1983. The hydrology and water quality of a drained clay catchment - Cockle Park, Northumberland. *Report RD/FE/10*, MAFF, London.

Armstrong, A.C. 1986. Drainage of clay lands for grass production: problems, effects, benefits. In Van Wijt, A.L.M. and Wesseling, J. (eds) *Agricultural Water Management*, Balkema, Rotterdam.

Armstrong, A.C., Atkinson, J.L. and Garwood, E.A. 1984. Grassland drainage economics experiment, N. Wyke, Devon. *Report RD/FE/23*, MAFF, London.

Armstrong, A.C. and Davies, P. 1984. The Cockle Park drainage experiment - Progress report for the year 1981-2. *Report RD/FE/18*, MAFF, London.

Armstrong, A.C. and Smith, Y. 1977. Soil series and drainage practices. *FDEU Technical Bulletin 77/5*, MAFF, London.

Arnell, N.W. 1989. Human influences on hydrological behaviour: an international literature survey. *Technical Documents in Hydrology*, Unesco Press, Paris.

Arrowsmith, R. 1983. The hydrology of the Hayes Oak Farm experimental site 1979-82. *Report RD/FE/16*, MAFF, London.

Arrowsmith, R., Armstrong, A.C., and Harris, G.L. 1989. The role of subsurface drainage in the generation of runoff from sloping clay land under different agricultural management regimes. *Second National Hydrology Symposium*, British Hydrological Society 1.23-1.36.

Avery, B.W. 1959. Geology and soils of the Grendon Underwood experimental catchment. Unpublished Soil Survey Report.

Avery, B.W. 1980. Soil classification for England and Wales. *Soil Survey Technical Monograph 14*, Rothamsted.

Avery, B.W. and Bascomb, C.L. 1974. Soil Survey laboratory methods. *Soil Survey Technical Monograph 6*, Rothamsted.

AWA, 1984. Lincoln flood alleviation scheme. Anglian Water Authority.

Baden, W. and Eggelsmann, R. 1964. Der Wasserkreislauf eines Nordwestdeutschen Hochmoores. (The water balance of some north west German raised bogs.) *Schriftenreihe des Kuratoriums für Kulturbauwesen 12*, Verlag Wasser und Boden, Hamburg.

Bailey, A.D. 1978. Agricultural drainage in England and Wales. *The Agricultural Engineer*, Winter 1978, 107-11.

Bailey, A.D. and Bree, T. 1981. Effect of improved land drainage on river flows. In: *Flood Studies Report - 5 Years On*. Thomas Telford, London, 131-42.

Bailey, A.D., Dennis, C.W., Harris, G.L. and Horner, M.W. 1980. Pipe size design for field drainage. *ADAS Research and Development Report No. 5*, FDEU, Cambridge.

Bailey Denton, J. 1862. On the discharge from underdrainage and its effects on the arterial channels and outfalls of the country. *Proc. Instn Civil Engineers* 21: 48-130.

Bailey Denton, J. 1873. Submission to the Select Committee of the House of Lords on the improvement of land. British Parliamentary Papers XVI.

Bailey Denton, J. 1881. Submission to the Royal Commission on the depressed condition of the agricultural interests 1880-2. British Parliamentary Papers XV.

Barsby, A. 1963. A wooden flume. *Technical Paper 28*, Water Research Association, Medmenham.

Bauer, J. 1977. Chairman of Grand River Conservation Authority, Ontario. Quoted in *Guelph Daily Mercury* 11th Feb 1977.

Bear, J. and Verruijt, A. 1987. *Modelling groundwater flow and pollution.* D. Reidel Publishing Co, Boston.

Beardmore, N. 1851. *Manual of Hydrology.* Waterlow and Sons, 2nd edn, London, 142.

Beardmore, N. 1862. *Manual of Hydrology.* Waterlow and Sons, 3rd edn, London, 148.

Beart, R. 1841. On the economical manufacture of draining tiles and soles. *J. Royal Agricultural Society* 2: 93-101.

van Beers, W.F.T. 1976. Computing drain spacings. International Institute for Land Reclamation and Improvement Bulletin 15, Wageningen.

Belding, E.T. 1971. Drainage survey in England and Wales. *Agriculture* 78: 250-54.

Beran, M.A., Farquharson, F.A.K. and Mandeville, A.N. 1982. River Witham system scheme Lincoln Flood alleviation: Hydrological studies. Report to Anglian Water Authority Ref RO 30663.

Beven, K.J. 1980. The Grendon Underwood field drainage experiment. *I.H. Report No. 65*, Wallingford.

Bibby, J.S., Douglas, H.A., Thomasson, A.J. and Robertson, J.S. 1982. Land classification for agriculture. The Macaulay Institute for Soil Research, Aberdeen.

Blackie, J.R. Ford, E.D., Horne, J.E.M., Kinsman, D.J.J., Last, F.T. and Moorhouse, P. 1980. Environmental effects of deforestation: an annotated bibliography. *Freshwater Biological Association Occasional Publication No. 10*, Ambleside.

Bloemen, G.W. 1974. On the evaluation of parameter values in water balance models. Institute for Land and Water Management Research, Technical Bulletin 92, Wageningen.

Blyth, K. and Nash, G.P. 1980. Aerial infrared photography and floodplain investigations. *J. Instn Wat. Engrs Scient.* 34: 425-34.

Boorman, D.B. 1985. A review of the Flood Studies Report rainfall runoff model parameter estimation equations. *I.H. Report No. 94*, Wallingford.

Boorman, D.B. and Reed, D.W. 1981. Derivation of a catchment average unit hydrograph. *I. H. Report No. 71*, Wallingford.

Bouma, J. 1986. Characterization of flow processes during drainage in some Dutch heavy clay soils. In Van Wijt A.L.M. and J. Wesseling (eds) *Agricultural Water Management*, Balkema, Rotterdam 3-11.

Bouwer, H. and van Schilfgaarde, J. 1963. Simplified method of predicting fall of water table in drained land. *Trans. Am. Soc. Agric. Engrs* 6: 288-91.

Bowers, K. 1985. British agricultural policy since the Second World War. *Agricultural History Review* 33: 66-76.

Brakensiek, D.L. 1977. Estimating the effective capillary pressure in the Green Ampt infiltration equation. *Wat. Resour. Res.* 13: 680-82.

Brakensiek, D.L., Engleman, R.L., and Rawls, W.J. 1980. Variations within texture classes of soil water parameters. Am. Soc. Agric. Engrs. Paper 80-2006.

Brakensiek, D.L. and Onstad, C.A. 1977. Parameter estimation of the Green and Ampt infiltration equation. *Wat. Resour. Res.* 13: 1009-12.

Bravo, N.J. and Schwab, 1977. Effect of openings on inflow into corrugated drains. *Trans. Am. Soc. Agric. Engrs.* 20: 100-4.

Bree, T. 1978. The stability of parameter estimation in the general linear model. *J. Hydrol.* 37: 46-66.

Bree, T. and Cunnane, C. 1980. The effect of arterial drainage on flood magnitude. *Casebook of methods of computation of quantitative changes in the hydrological regime of river basins due to human activities.* Unesco Press, Paris 116-25.

Broadhead, R.G. and Skaggs, R.W. 1982. Drainage strategies and peak flood flows. *Am. Soc. Agric. Engrs.* Paper 82-2054.

Brooke, J.S. 1983. Non-stationarity in the flooding response of the Upper River Witham. Unpublished BSc dissertation, Huddersfield Polytechnic.

Brookes, A. 1981. Channelization in England and Wales. Discussion Paper 11, Department of Geography, University of Southampton.

Brookes, A. 1988. *Channelised rivers.* J. Wiley and Sons, Chichester.

Brookes, A., Gregory, K.J., and Dawson, F.H. 1983. An assessment of river channelization in England and Wales. *Sci. of the Total Environ.* 27: 97-111.

BSI, 1965. Measurement of liquid flow in open channels. BS3680, Part 4A. Thin plate weirs and venturi flumes. British Standards Institution, London.

BSI, 1967. Methods of test for soils for civil engineering purposes. BS1377, British Standards Institution, London.

Burke, J.F. 1841. On the drainage of land. *J. Royal Agricultural Society of England* 2: 273-96.

Burke, W. 1968. Drainage of blanket peat at Glenamoy. *Proc. 2nd International Peat Congress*, HMSO Edinburgh 2: 809-17.

Burke, W. 1975. Aspects of the hydrology of blanket peat in Ireland. International Association of Hydrological Sciences 105: 171-181.

Burke, W., Gabriels, D. and Bouma, J. 1986 (eds). *Soil Structure Assessment.* AA Balkema, Rotterdam.

Burke, W., Mulqueen, J. and Butler, P. 1974. Aspects of the hydrology of a gley on a drumlin. *Irish J. Agric. Res.* 13: 215-228.

Caird, J. 1873. Submission to the Select Committee of the House of Lords on the Improvement of Land. British Parliamentary Papers XVI.

Calder, I.R., Harding, R.J. and Rosier, P.T.W. 1983. An objective assessment of soil moisture deficit models. *J. Hydrol.* 60: 329-355.

Campbell, K.L., Kumar, S. and Johnson, H.P. 1972. Stream straightening effects on flood runoff characteristics. *Trans. Am. Soc. Agric. Engrs* 15: 94-98.

Cannell, R.Q., Goss, M.J., Harris, G.L., Jarvis, M.G., Douglas, J.T., Howse, K.R. and Le Grice, S. 1984. A study of mole drainage with simplified cultivation for autumn-sown crops on a clay soil. I Background, experiment and site details, drainage systems, measurement of drainflow and summary of results, 1978-81. *J. Agric. Sci.* 102: 539-559.

Carlston, C.W. 1963. Drainage density and streamflow. US Geological Survey Professional Paper 442C, Washington.

Castle, D.A., McCunnall, J. and Tring, I.M. (eds) 1984. *Field Drainage: Principles and Practices.* Batsford, London.

Caufield, C. 1982. Too much drainage spells trouble on t'farm. *New Scientist*, 21st January 1982, 125.

Chambers, J.D. and Mingay, G.E. 1966. The Agricultural Revolution.

Chang, A.C., Skaggs, R.W., Hermsmeier, L.F. and Johnston, W.R. 1983. Evaluation of a water management model for irrigated agriculture. *Trans. Am. Soc. Agric. Engrs* 26: 412-22.

Childs, E.C. 1943. Studies in mole draining - interim report on an experimental drainage field. *J. Agric. Sci.* 33: 136-146.

Childs, E.C. 1969. *An Introduction to the Physical Basis of Soil Water Phenomena*. J. Wiley & Sons, London.

Childs, E.C. and Bybordi, M. 1969. The vertical movement of water in stratified porous material: 1 Infiltration. *Wat. Resour. Res.* 5: 446-459.

Clapp, R.B. and Hornberger, G.M. 1978. Empirical equations for some soil hydraulic properties. *Wat. Resour. Res.* 14: 601-4.

Clapperton, C.M. (ed) 1983. *Scotland, a New Study*. David and Charles, Newton Abbot.

Clayden, B. and Hollis, J.M. 1984. Criteria for differentiating soil series. *Soil Survey Technical Monograph 17*. Soil Survey of England and Wales, Harpenden.

Cole, G. 1976. Land drainage in England and Wales. *J. Instn Wat. Engrs Scient.* 30: 345-367.

Conway, V.M. and Millar, A. 1960. The hydrology of some small peat covered catchments in the N. Pennines. *J. Instn Wat. Engrs* 14: 415-424.

Coppock, J.T. 1976a. *An Agricultural Atlas of England and Wales*. Faber and Faber, London 2nd edn.

Coppock, J.T. 1976b. *Agricultural Atlas of Scotland*. J. Donald, Edinburgh.

Corey, A.T. 1977. *Mechanics of Heterogeneous Fluids in Porous Media*. Water Resources Publications, Fort Collins.

Cox, D.R. and Lewis, P.W. 1966. *The Statistical Analysis of Series of Events*. Methuen, London.

Cunnane, C. 1973. A particular comparison of annual maxima and partial duration series methods of flood frequency prediction. *J. Hydrol.* 18: 257-272.

Dennis, C.W. and Trafford, B.D. 1975. The effect of permeable surrounds on the performance of clay field drainage pipes. *J. Hydrol.* 24: 239-49.

DoE. 1986. Nitrate in water. Department of the Environment Pollution Paper No. 26, HMSO, London.

De Jong, R. 1981. Soil water models: a review. Land Resource Research Institute, Contribution 125, Ottawa, Canada.

Dieleman, P.J. and Trafford, B.D. 1976. Drainage testing. Irrigation and Drainage Paper 28, Food and Agriculture Organisation, Rome.

Diskin, M.H. and Boneh, A. 1975. Determination of an optimal IUH for linear, time-invariant systems from multi-storm records. *J. Hydrol.* 24: 57-76.

Dooge, J.C.I. 1973. Linear theory of hydrologic systems. US Department of Agriculture Technical Bulletin 1486.

Douglas, J.T., Goss, M.J. and Hill, D. 1980. Measurements of pore characteristics in a clay soil under ploughing and direct drilling, including the use of a radioactive tracer technique. *Soil and Tillage Research* 1: 11-18.

Edwards, K.A. and Rodda, J.C. 1970. A preliminary water balance of a small clay catchment. *J. Hydrol.* (NZ) 9: 202-18.

Eeles, C.W.O. 1978. A conceptual model for the estimation of historic floods. *I.H. Report No. 55*, Wallingford.

Egglesmann, R. 1971. Uber den hydrologischen Einfluss der Moore (About the hydrological effect of moors). Telma 1: 37-48.

Egglesmann, R. 1978. *Subsurface Drainage Instructions*. Verlag Paul Parey, Hamburg.

Emerson, J.W. 1971. Channelisation: a case study. *Science* 173: 325-26.

Engel, H. 1985. Anthropogene Einflüsse auf die Hochwasser - Abflussverhältnisse des Rheins bis zum Pegel Kaub (Anthropogenic effects on the flood discharge regime on the Rhine at the Kaub gauging station). Kurzdokumentation der Arbeiten von Hochwasserstudien kommission für den Rhein, Koblenz.

Essery, C.I. and Wilcock, D.N. 1990. The impact of channelisation on the hydrology of the upper river Main, County Antrim, Northern Ireland - a long term case study. *Regulated Rivers: Research and Management* 5: 17-34.

Evans, N. 1984. Channelisation effects in Great Langdale Beck, Cumbria. Unpublished BSc project, Department of Geography, University of Hull.

Farquharson, F.A.K. 1976. Recording raingauge catalogue for the UK - is yours in it? *Weather* 31: 203.

Farr, E. and Henderson, W.C. 1986. *Land Drainage*. Longman, London.

Farquharson, F.A.K., Mackney, D., Newson, M.D. and Thomasson, A.J. 1978. Estimation of runoff potential of river catchments from soil surveys. Special Survey No. 11, Soil Survey of England and Wales, Harpenden.

Findlay, D.C., Colborne, G.J.N., Cope, D.W., Harrod, T.R., Hogan, D.V. and Staines, S.J. 1984. Soils and their use in SW England. Soil Survey of England and Wales Bulletin No. 14, Harpenden.

Fleming, G. 1973. Flood frequency and the effects of catchment changes. *Wat. Wat. Engng* 77:127-31.

Forbes, T.J., Dibb, C., Green, J.O., Hopkins, A. and Peel, S. 1980. Factors affecting the productivity of permanent grassland. Joint Permanent Pasture Group, Hurley, Maidenhead.

Foster, I.D.L. (ed) 1989. Soil erosion on agricultural land. Field excursion guide to the N Warwickshire and NW Midlands experimental sites, British Geomorphological Research Group Jan 1989 Meeting.

Found, W.C., Hill, A.R. and Spence, E.S. 1974. Economic and environmental impacts of land drainage in Ontario. Geographical Monograph 6 York University, Toronto.

Framji, K.K., Garg, B.C. and Luthra, S.D.L. (eds) 1982. *Irrigation and Drainage in the World, a Global Review.* 3rd edn. International Commission on Irrigation and Drainage, New Delhi.

Francis, I.S. 1987. Blanket peat erosion in mid Wales: two catchment studies. Unpublished PhD thesis, University of Wales.

Furness, R.R. 1985. Soils in Humberside, I: Brandesburton. Soil Survey Record No. 82, Soil Survey of England and Wales, Rothamsted.

Galvin, L.F. 1969. Land drainage survey II. *Irish J. Agric. Res.* 8: 1-18.

Galvin, L.F. 1971. Land drainage survey III: maps of Ireland showing the general distribution of drainage problems and of drainage schemes. *Irish J. Agric. Res.* 10: 213-220.

Galvin, L.F. 1986. Impermeable soils require stable channels and good crack formation for effective drainage. In Smith, K.V.H. and Rycroft, D.W. (eds) *Hydraulic Design in Water Resources Engineering: Land Drainage.* Springer-Verlag, New York 413-22.

Germann, P. and Beven, K.J. 1981. Water flow in macropores, I An experimental approach. *J. Soil Sci.* 32: 1-13.

Goss, M.J., Howse, K.R. and Harris, W. 1978. Effects of cultivation on soil water retention and water use by cereals in clay soils. *J. Soil Sci.* 29: 475-88.

Green, F.H.W. 1958. Problems raised by the operation of, and the results from, a small network of British evaporation measuring stations. International Association of Scientific Hydrology 45: 444-461.

Green, F.H.W. 1973. Aspects of the changing environment: some factors affecting the aquatic environment in recent years. *J. Environ. Management* 1: 377-391.

Green, F.H.W. 1974. Changes in artificial drainage, fertilisers and climate in Scotland. *J. Environ. Management* 2: 107-21.

Green, F.H.W. 1975. Ridge and furrow, mole and tile. *Geographical J.* 141: 88-93.

Green, F.H.W. 1976. Recent changes in land use and treatment. *Geographical J.* 142: 12-26.

Green, F.H.W. 1977. Current trends in field drainage practice. *J. Environ. Management* 5: 207-213.

Green, F.H.W. 1979a. Field, forest and hill drainage in Scotland. *Scottish Geographical Magazine* 95: 159-64.

Green, F.H.W. 1979b. Field drainage in Europe: a quantitative survey. *I.H. Report No. 57,* Wallingford.

Green, F.H.W. 1980a. Current field drainage in northern and western Europe. *J. Environ. Management* 10: 149-153.

Green, F.H.W. 1980b. Field underdrainage before and after 1940. *Agricultural History Review* 28: 120-23.

Green, W.H. and Ampt, G.A. 1911. Studies in soil physics, part I. The flow of air and water through soils. *J. Agric. Sci.* 4: 1-24.

Haines, L.W. 1965. Report by the engineer to the Board on the December 1964 flood in the Severn valley, with particular reference to Newtown, Montgomeryshire. Severn River Board, Malvern.

Hall, D.G.M., Reeve, M.J., Thomasson, A.J. and Wright, V.F. 1977. Water retention, porosity and density of field soils. Soil Survey Technical Monograph 9.

Hansard. 1983. York (flooding). House of Commons Parliamentary Debates, *Weekly Hansard* 17(1231): 1089-94.

Harms, R.W. 1986a. The effects of artificial subsurface drainage on flood discharge. In Smith, K.V.H. and Rycroft, D.W. (eds) *Hydraulic Design in Water Resources Engineering: Land Drainage.* Computational Mechanics Publication, Southampton 189-98.

Harms, R.W. 1986b. *Langzeitsimulation zur Untersuchung des Einflusses von Melioration auf den Hochwasserabluss.* (Long-term simulation to study the effect of agricultural improvement on high flows). Institut für Wasserwirtschaft, Hydrologie und landwirtschaftlichen Wasserbau der Universität, Hannover, Abschlussbericht Lotto 13/82.

Harris, G.L. (ed) 1977. A progress report on FDEU sites for 1976. *FDEU Technical Bulletin 77/7,* MAFF, London.

Harris, G.L., Goss, M.J., Dowdell, R.J., Howse, K.P. and Morgan, P. 1984. A study of mole drainage with simplified cultivation for autumn sown crops on a clay soil. II Soil water regimes, water balances and nutrient loss in drain water, 1978-80. *J. Agric. Sci.* 102: 561-581.

Harrold, L.L. and Edwards, W.M. 1972. A severe rainstorm test of no-till corn. *J. Soil Wat. Conservation* 27: 30.

Hart, I.D.M. 1979. The effects of altering runoff characteristics. Letter to *New Civil Engineer* 66.

Haslam, S.M. 1978. *River Plants*. Cambridge University Press.

Hazen, A. 1930. *Flood Flows*. J. Wiley, New York.

Henderson, W.C. 1973. Agricultural drainage problems in the North East. *Scottish Agriculture* 51: 506-11.

Hewlett, J.D. 1982. *Principles of Forest Hydrology*. University of Georgia.

Higgins, G.M., Dieleman, P.J. and Abernethy, C.L. 1988. Trends in irrigation development, and their implications for hydrologists and water resources engineers. *Hydrol. Sci. J.* 33: 43-59.

Higgs, G. 1987. Environmental change and flood hazard in the upper Severn. Unpublished PhD thesis, University of Wales.

Higgs, G. and Petts, G. 1988. Hydrological changes and river regulation in the UK. *Regulated Rivers: Research and Management* 2: 349-68.

Hill, A.D. 1942. *Reconstruction and the Land*. Macmillan and Co, London.

Hillel, A. and Gardner, W.R. 1969. Steady infiltration into crust topped profiles. *Soil Science* 108: 137-42.

Hillman, E.C. 1936. The effect of flood relief works on flood levels below such works. *J. Instn Civil Engrs*, 2: 393-411.

Hinson, W.H., Fourt, D.F. and Binns, W.O. 1973. The use and abuse of borehole studies in forest drainage research. Forestry Commission, Alice Holt.

HMSO. 1975. Food from our own resources. HMSO, London.

HMSO. 1979. Agricultural Statistics Act 1979. HMSO, London.

Hockin, D.L. 1985. The impact of channelization: some engineering aspects. *Geogr. J.* 151: 53-74.

Hodgson, J.M. (ed) 1974. Soil Survey field handbook: describing sampling and soil profiles. Soil Survey Technical Monograph 5. Soil Survey of England and Wales, Harpenden.

Hoffman, G.J. and Schwab, G.O. 1964. Tile spacing predictions based on drain outflow. *Trans. Am. Soc. Agric. Engrs.* 7: 444-7.

Howe, G.M., Slaymaker, H.O. and Harding, D.M. 1967. Some aspects of the flood hydrology of the upper catchments of the Severn and Wye. *Trans. Inst. British Geographers* 41: 33-58.

IH. 1979. Short cut to unit hydrograph convolution. *Flood Studies Supplementary Report* 9, Institute of Hydrology, Wallingford.

IH. 1986. *Hydrological Research in the UK.* Institute of Hydrology, Wallingford. (Published every five years since 1965.)

IH. 1988. Hydrometric register and statistics, 1981-5. *Hydrological Data: UK Series*, Institute of Hydrology, Wallingford.

Irwin, R.W. and Whiteley, H.R. 1983. Effects of land drainage on streamflow. *Canadian Wat. Resour. J.* 8: 88-103.

Jarvis, M.G. 1973. Soils of the Wantage and Abingdon district. *Memoirs of the Soil Survey of Great Britain*, Harpenden.

Jarvis, R.A., Bendelow, V.C., Bradley, R.I., Carroll, D.M., Furness, R.R., Kilgour, I.N.L. and King, S.J. 1984. Soils and their use in N England. *Soil Survey of England and Wales Bulletin No. 10*, Harpenden.

Johnson, P. 1975. Snowmelt. Floods Studies Conference, Institution of Civil Engineers, London 5-10.

Johnson, P. 1981. The future of flood estimation and the Flood Studies Report. *Proc. Instn Civil Engrs*, Part I 70: 833-43.

Kendall, R.G. 1950. *Land Drainage*. Faber and Faber, London.

Kirkham, D. 1957. Theory of land drainage: the ponded water case. In Luthin, J.N. (ed) *Drainage of Agricultural Lands. Agricultural Monograph 7*, American Society of Agronomy 139-81.

Klute, A. (ed) 1986a. Methods of soil analysis, I Physical and mineralogical methods. *Agronomy 9*. American Society of Agronomy/Soil Science Society of America, 2nd edn Madison, Wisconsin.

Klute, A. 1986b. Water retention, laboratory methods. Ch 26 in : Klute, A. 1986a *op cit.* 635-62.

Kneale, W.R. 1983. The movement of water and solutes in the structural clay soil of the Wytham catchment. Unpublished D.Phil. thesis, Dept of Agriculture and Forest Science, Oxford University.

Konyha, K.D., Robbins, K.D. and Skaggs, R.W. 1988a. Evaluating peat-mining hydrology using DRAINMOD. *J. Irrig. Drain. Engng*, 114: 490-504.

Konyha, K.D., Skaggs, R.W. and Gilliam, J.W. 1988b. Hydrologic impacts of agricultural water management. In Hook, D.D. (ed) *The Ecology and Management of Wetlands Vol 2: Management, Use and Value of Wetlands.* Croom Helm Publishers, London 148-59.

Kuipers, H. and van Ouwerkerk, C. 1963. Total pore space estimations in freshly ploughed soil. *Netherlands J. Agric. Sci.* 11: 45-53.

Lambert, A.O. 1969. A comprehensive rainfall runoff model for an upland catchment. *J. Instn Wat. Engrs* 23: 231-39.

Lea, J.W. 1975. Soils in Powys I. Soil Survey Record No. 28, Soil Survey of England and Wales, Rothamsted.

Learmounth, A.T.A. 1950. The floods of 12th August 1948, in south-east Scotland. *Scottish Geographical Magazine* 66: 147-53.

Leeds-Harrison, P., Spoor, G. and Godwin, R.J. 1982. Water flow to mole drains. *J. Agric. Engng Res.* 27: 81-91.

Leeks, G.J.L. and Roberts, G. 1987. The effects of forestry on upland streams - with special reference to water quality and sediment transport. In Good, J.E.G. (ed) *Environmental Aspects of Plantation Forestry in Wales.* Institute of Terrestrial Ecology Symposium 22: 9-24.

Lencastre, A. 1987. *Handbook of Hydraulic Engineering.* Ellis Horwood Ltd, Chichester.

Lewin, J. 1976. Assessment of channel change on Welsh rivers. *Cambria 3*: 1-10.

Lewis, W.K. 1957. Investigation of rainfall, runoff and yield on the Alwen and Brenig catchments. *Proc. Instn Civil Engrs* 8: 17-51.

Lindstrom, M.J. and Onstad, C.A. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. *J. Soil and Water Conservation* 39: 149-152.

Linsley, R.K., Kohler, M.A. and Paulhus, J.L.M. 1975. *Hydrology for Engineers.* McGraw-Hill, New York.

Lowing, M.J. and Newson, M.D. 1973. Flood event data collation. *Wat. Wat. Engng* March, 3-7.

Luthin, J.N. 1957. *The Drainage of Agricultural Land.* American Society of Agronomy, Madison, Wisconsin.

Lynn, M. 1981. Estimating the flood magnitude return period relationships and the effect of catchment drainage. Office of Public Works, Hydrology Unit Report Dublin.

McCubbin, G.A. 1938. Agricultural drainage in southwestern Ontario. *Engineering J.* 21: 66-70.

McDonald, A. 1973. Some views on the effect of peat drainage. *Scottish Forestry* 27: 315-27.

Mackay, C. (Chairman) and eight others, 1973. Drainage of agricultural land in Scotland. Report of Working Group, DAFS, Edinburgh.

MAF. 1951. Land drainage in England and Wales. Report of the Land Drainage Legislation Sub-Committee of the Central Advisory Water Committee. HMSO, London.

MAFF. 1977. Agricultural land classification of England and Wales: 1:125000 series explanatory note. HMSO, London.

MAFF. 1979. Arterial drainage and agriculture. Getting down to drainage. Leaflet 16, MAFF (publications), Pinner.

MAFF. 1982. *The Design of Field Drainage Pipe Systems*. Reference Book 345, HMSO, London.

MAFF. 1986. A guide to the development of grants for agriculture and horticulture in England and Wales, 1940-85. Economics (Resource Use) Division, MAFF, London.

MAFF. 1988. *Set Aside; A Practical Guide*. MAFF SA 6, London.

Mandeville, A.N., O'Connell, P.E., Sutcliffe, J.V. and Nash, J.E. 1970. River flow forecasting through conceptual models: Part III - The Ray catchment at Grendon Underwood. *J. Hydrol.* 11: 109-28.

Marks, H.F. and Britton, D.K. 1989. *A Hundred Years of British Food and Farming: a Statistical Survey*. Taylor and Francis, London.

Marshall, T.J. and Holmes, J.W. 1979. *Soil Physics*. Cambridge University Press.

Marshall, E.J.P., Wade, P.M. and Clare, P. 1978. Land drainage channels in England and Wales. *Geogr. J.* 144: 254-63.

May, B.R. and Hitch, T.J. 1989. Improved values of 1-hour M5 rainfalls for the United Kingdom. *Met. Mag.* 118: 76-81.

Mein, R.G. and Larson, C.L. 1973. Modelling infiltration during a steady rain. *Wat. Resour. Res.* 9: 384-94.

Miers, R.H. 1979. Land drainage - its problems and solutions. *J. Instn Wat. Engrs Scient.* 33: 547-79.

Miller, J.B. and Newson, M.D. 1975. Flood estimation from catchment characteristics. Flood Studies Conference, Institution of Civil Engineers, London 57-60.

Mishra, A., Parker, J.C. and Singhal, N. 1989. Estimation of soil hydraulic properties and their uncertainty from particle size distribution data. *J. Hydrol.* 108: 1-18.

Mitchell, G.S. 1898. *A Handbook of Land Drainage*. Land Agents Record Ltd, London 2nd edn.

Moody, W.T. 1966. Nonlinear differential equation of drain spacing. *J. Irrig. Drain. Div.* 92(IR2): 1-9.

Moore, P. and Grace, F. 1989. River Foss flood alleviation scheme. *Association of Drainage Authorities Gazette*, Summer 1989: 7-9.

Moore, W.L. and Morgan, C.W. (eds) 1969. Effects of watershed changes on streamflow. *Centre for Research in Water Resources, Water Resources Symposium* 2, University of Texas Press, Austin and London.

Morland, B. 1989. *Anglers' Directory.* Treasure Press, 3rd edn.

Morris, J. and Hess, T.M. 1984. Drainage benefits and farmer uptake. MAFF Conference of River Engineers, Cranfield, July 1984.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Wat. Resour. Res.* 12: 513-22.

Muir, R. 1987. *History from the Air.* Mermaid Books Ltd, London.

Nash, J.E. 1960. A unit hydrograph study with particular reference to British catchments. *Proc. Instn Civil Engineers* 17: 249-82.

National Water Council. 1982. Water industry review 1982, supporting analysis. London.

Nemec, J. 1976. Time variability of hydraulic conductivity in heavy clay soils. *Proc. Bratislava Symp. on Water in Heavy Clay Soils,* 2: 81-92.

NERC. 1975. *Flood Studies Report.* Natural Environment Research Council, London, 5 volumes.

Newson, M.D. 1975a. *Flooding and Flood Hazard in the United Kingdom.* Oxford University Press, London.

Newson, M.D. 1975b. Mapwork for flood studies. Part I: Selection and derivation of indices. *I.H. Report No. 25,* Wallingford.

Newson, M.D. 1980. Water balances at selected sites. In Doornkamp, J.C. and Gregory, K.J. (eds) *Drought Atlas.* Institute of British Geographers, London 37-38.

Newson, M.D. and Robinson, M. 1983. Effects of agricultural drainage on upland streamflow; case studies in mid-Wales. *J. Environmental Management* 17: 333-348.

Nicholson, H.H. 1943. Modern field drainage. *J. Royal Agricultural Society of England* 104: 118-35.

Nicholson, H.H. 1953. *The Principles of Field Drainage.* Cambridge University Press, 2nd edn.

Nicholson, I.A., Robertson, R.A. and Robinson, M. 1989. The effects of drainage on the hydrology of a peat bog. *International Peat J.* 3: 59-83.

Nolte, B.H. 1986. Documentation for the water management simulation program DRAINMOD. In Saavalainen, J. and Vakkilainen, P. (eds) *Proc. International Seminar on Land Drainage,* Helsinki University of Technology 283-87.

O'Kelly, J.J. 1945. Rainfall and runoff in relation to arterial drainage. *Trans. Instn Civil Engineers of Ireland* 72: 23-51.

O'Kelly, J.J. 1955. The employment of unit hydrographs to determine the flows of Irish arterial drainage channels. *Proc. Instn Civil Engineers* 4: 365-445.

Oberlin, G. 1981. Influence du drainage et de l'assainissement rural sur l'hydrologie. *CEMAGREF Bulletin* 285: 45-56.

Oldfield, P. 1983. Drain and be damned. *Guardian* 9th April 1983.

Oracle. 1985. Product summary and technical documentation. Oracle Corporation UK Ltd, Richmond, Surrey, 3 Vols.

Paivanen, J. 1973. Hydraulic conductivity and water retention in peat soils. *Acta Forestalia Fennica* 129: 1-68.

Paivanen, J. 1976. Effect of different types of contour ditches on the hydrology of an open bog. 5th International Peat Congress, International Peat Society 93-106.

Parker, A. 1983. Benefits and economics of grassland drainage. *Report RD/FE/14*, MAFF, London.

Pearson, E.S. and Hartley, H.O. 1972. *Biometrica Tables for Statisticians*. The University Press, Cambridge.

Penning-Rowsell, E.C., Parker, D.J. and Harding, D.M. 1986. *Floods and Drainage*. Allen and Unwin, London.

Pickels, G.W. 1925. *Drainage and Flood Control Engineering*. McGraw-Hill Book Co, New York.

Pickels, G.W. 1931. University of Illinois Bulletin (Quoted by McCubbin, 1938).

Plinston, D.R. and Hill, A. 1974. A system for the quality control and processing of streamflow, rainfall and evaporation data. *I.H. Report No. 15*, Wallingford.

Price, R.K. 1977. FLOUT - A river catchment flood model. *Hydraulics Research Station Report* IT 168 (revised Jan 1980), Wallingford.

Pusey, P. 1841. A note on the economical manufacture of draining tiles and soles. *J. Royal Agricultural Society of England* 2: 101-4.

Quisenberry, V.L. and Phillips, R.E. 1976. Percolation of surface applied water in the field. *Proc. Soil Science Society of America* 40: 384-89.

Raistrick, A. 1967. *Old Yorkshire Dales*. David and Charles, London.

Rands, J.G. 1973. An analysis of drainflow at FDEU experimental sites. *FDEU Technical Bulletin 73/11*. MAFF, London.

Rawls, W.J., Brakensiek, D.L. and Saxton, K.E. 1982. Estimation of soil water properties. *Trans. Am. Soc. Agric. Engrs* 25: 1316-20.

Reeves, M. and Miller, E.E. 1975. Estimating infiltration for erratic rainfall. *Wat. Resour. Res.* 11: 102-10.

Refsgaard, J.C. 1987. A methodology for distinguishing between the effects of human influence and climate variability on the hydrologic cycle. International Association of Hydrological Sciences 168: 557-70.

Reid, I. and Parkinson, R.J. 1984. The nature of the tile drain outfall hydrograph in heavy clay soils. *J. Hydrol.* 72: 289-305.

Rhodes, L.A. 1950. Engineer's report on problems in connection with drainage and flooding within the area of the Board, a brief review of the works of the late River Severn Catchment Board and suggested future major improvement schemes. Severn River Board, Great Malvern.

Riddington, D. J. 1989. From the Chairman. *Association of Drainage Authorities Gazette*, Summer 1989.

Riley, J.P., Chadwick, D.G. and Israelsen, E.K. 1963. Watershed simulation by electronic analogue computer. International Association of Hydrological Sciences 80: 25-37.

Rimington, D. 1982. Down the drain. Letter in *Yorkshire Post*, 8th February 1982.

Roberts, A.M. 1989. The catchment research data base at the Institute of Hydrology. *I.H. Report No. 106*, Wallingford.

Roberts, G. 1981. The processing of hydrological data. *I.H. Report No. 70*, Wallingford.

Robertson, R.A., Nicholson, I.A. and Hughes, R. 1968. Runoff studies on a peat catchment. *Proc. 2nd International Peat Congress*, HMSO, London 161-166.

Robinson, G.W. 1984. Weed control in drainage channels with special reference to conservation. MAFF Conference of River Engineers, Cranfield.

Robinson, M. 1985. Farm drainage - a cause of flooding? *Agricultural and Advisory Service Bulletin* 159, MAFF, Oxford 10-12.

Robinson, M. 1986a. The extent of farm underdrainage in England and Wales, prior to 1939. *The Agricultural History Review* 34: 77-85.

Robinson, M. 1986b. Changes in catchment runoff following drainage and afforestation. *J. Hydrol.* 86: 71-84.

Robinson, M. 1987. Agricultural drainage can alter catchment flood frequency. *National Hydrology Symposium*, British Hydrological Society, London 6.1 - 6.10.

Robinson, M. 1989a. Small catchment studies of Man's impact on flood flows: agricultural drainage and plantation forestry. *International Association of Hydrological Sciences Publication 187*, 299-308.

Robinson, M. 1989b. Storm flow changes due to artificial drainage. In Gustard, A., Roald, L.A., Demuth, S., Lumadjeng, H.S. and Gross, R. (eds) *Flow Regimes from Experimental and Network Data (FREND)* Institute of Hydrology, Wallingford 223-34.

Robinson, M. and Armstrong, A.C. 1988. The extent of agricultural field drainage in England and Wales, 1971-80. *Trans. Inst. British Geographers* 13: 19-28.

Robinson, M. and Beven, K.J. 1983. The effect of mole drainage on the hydrological response of a swelling clay soil. *J. Hydrol.* 63: 205-223.

Robinson, M., Clayton, M.C. and Henderson, W.C. 1990. The extent of agricultural field drainage in Scotland, 1983-6. *Scottish Geographical Magazine* 106: 141-7.

Robinson, M., Eeles, C.W.O. and Ward, R.C. 1990. The research basin and stationarity. *Proc. TNO Committee on Hydrological Research No 44*, Wageningen, The Netherlands 113-21.

Robinson, M., Mulqueen, J. and Burke, W. 1987. On flows from a clay soil - seasonal changes and the effect of mole drainage. *J. Hydrol* 91: 339-350.

Robinson, M., Ryder, E.L. and Ward, R.C. 1985. Influence on streamflow of field drainage in a small agricultural catchment. *J. Agric. Wat. Management* 10: 145-8.

Robson, J.D. and Thomasson, A.J. 1977. Soil water regimes. *Soil Survey Technical Monograph 11.*

Rodda, J.C. 1976. Basin studies. In Rodda, J.C. (ed) *Facets in Hydrology*. J. Wiley, Chichester 257-97.

Roy, M.G. and Hough, M.N. 1978. Effects of weather and climate on modern British farming. *J. Royal Agricultural Society* 139: 43-53.

Rudeforth, C.C., Hartnup, R., Lea, J.W., Thompson, T.R.E. and Wright, P.S. 1984. Soils and their use in Wales. *Soil Survey of England and Wales Bulletin No. 11*, Harpenden.

Rycroft, D.W. and Massey, W. 1975. The effect of field drainage on river flow. *FDEU Technical Bulletin 75/9*, MAFF, London.

Ryder, E.L. 1979. The role of tile drainage in the hydrology of a site comprising 45 acres of agricultural land in Holderness. Unpublished report, Department of Geography, University of Hull.

Sampson, R.J. 1978. Surface II graphics system. Kansas Geological Survey.

Sangvaree, W. and Yevjevich, V. 1977. Effects of forest and agricultural land use on flood unit hydrographs. Hydrology Paper 92, Colorado State University.

Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.I. 1986. Estimating generalized soil water characteristics from texture. *Soil Science Society of America J.* 50: 1031-6.

Schuch, M. 1976. Water regime of a cultivated, an untouched and an afforested peat land near the Alps. 5th International Peat Congress 887-892.

Schuch, M. 1978. Regulation of water regime of heavy soils by drainage, subsoiling and liming and water movement in this soil. Paper 1.14 in Wesseling J. (ed) *Proc. International Drainage Workshop*, May 1978. International Institute for Land Reclamation and Improvement, Wageningen, 253-67.

Serrano, S.E., Whiteley, H.R. and Irwin, R.W. 1985. Effects of agricultural drainage on streamflow in the Middle Thames River, Ontario, 1949 - 1980. *Canadian J. Civil Engineering* 12: 875-85.

Shaw, E.M. 1988. *Hydrology in Practice*. Van Nostrand Reinhold, Wokingham.

Skaggs, R.W. 1976. Determination of the hydraulic conductivity - drainable porosity ratio from water table measurements. *Trans. Am. Soc. Agric. Engrs* 19: 73-80.

Skaggs, R.W. 1980. A water management model for artificially drained soils. *Technical Bulletin 267*, N Carolina Agricultural Research Service.

Skaggs, R.W. 1981. DRAINMOD reference report: Methods for the design and evaluation of drainage water management systems for soils with high water tables. Soil Conservation Service, US Department of Agriculture, Fort Worth, Texas.

Skaggs, R.W. 1982. Field evaluation of a water management simulation model. *Trans. Am. Soc. Agric. Engrs* 25: 666-74.

Skaggs, R.W. 1986. Drainage modelling in research and design. In Saavalainen, J. and Vakkilainen, P. (eds) *Proc. International Seminar on Land Drainage*, Helsinki University of Technology 153-80.

Skaggs, R.W., Fausey, N.R. and Nolte, B.H. 1981. Water management model evaluation for N Central Ohio. *Trans. Am. Soc. Agric. Engrs* 24: 922-8.

Skaggs, R.W. and Nassehzadeh-Tabrizi, A. 1984. Can we afford to design field drainage systems? Paper 84-2568 Winter meeting Am. Soc. Agric. Engrs.

Smedema, L.K. and Rycroft, D.W. 1983. *Land Drainage*. Batsford, London.

Smith, L.P. 1967. Potential transpiration. *MAFF Technical Bulletin 16*, London.

Smith, L.P. and Trafford, B.D. 1976. Climate and drainage. *MAFF Technical Bulletin 34*, HMSO, London.

Spoor, G. and Fry, R.K. 1983. Field performance of trenchless drainage tines and implications for drainage system efficiency *J. Agric. Engng Res.* 28: 319-35.

Spoor, G. and Godwin, R.J. 1978. An experimental investigation into deep loosening of soil by rigid tines. *J. Agric. Engng Res.* 23: 243-58.

Stansfield, C. 1987. Field drainage 1940-84 - a success but where to now? *Soil and Water* 15: 12-13.

Stewart, A.J.A. and Lance, A.N. 1983. Moor draining: a review of impacts on land use. *J. Environmental Management* 17: 81-99.

Stewart, L. 1963. Investigations into migratory fish propagation in the area of the Lancashire River Board. John B. Barber & Sons, Lancaster.

Strangeways, I.C. and Templeman, R.F. 1974. Logging river level on magnetic tape. *Water Services* 78: 57-60.

Strutt, N. 1970. (Chairman) Modern farming and the soil. Report of the Agricultural Advisory Council on Soil Structure and Soil Fertility. HMSO, London.

Sturgess, R.W. 1966. The Agricultural Revolution on the English Clays. *Agricultural History Review* 14: 104-21.

Sturgess, R.W. 1967. The Agricultural Revolution on the English Clays: a rejoinder. *Agricultural History Review* 15: 82-7.

SSEW. 1983. Soil survey map of England and Wales at 1: 250,000 scale. Sheets 1-6. Soil Survey of England and Wales, Rothamsted.

SSEW. 1986. Annual Report. Soil Survey of England and Wales, Rothamsted.

SSS. 1982. The soils and land capability for agriculture. Maps 1-7 scale 1: 125,000 Soil Survey of Scotland, Macaulay Institute for Soil Research, Aberdeen.

Swales, S. 1982. Environmental effects of river channel works used in land drainage improvement. *J. Environmental Management* 14: 103-26.

Tang, D.Y. and Ward, R.C. 1982. Aspects of evapotranspiration and the water balance in a small clay catchment 1967-75. *Weather* 37: 194-201.

Taylor, G.S. 1960. Drainable porosity evaluation from outflow measurements and its use in drawdown equations. *Soil Science* 90: 338-43.

Taylor, G.S., Hundall, S.S., Fausey, N.R. and Schwab, G.O. 1981. Backfill alteration effects on pipe drainage of a clay soil. *Soil Science Society of America J.* 45: 611-16.

Thomasson, A.J. 1975. Hydrological and environmental aspects. Ch 7 in Thomasson, A.J. (ed) Soils and field drainage. *Technical Monograph No.* 7, Soil Survey of England and Wales, Harpenden 62-65.

Thompson, C.K. 1948. Hill drainage. *J. British Grassland Society* 3: 193-201.

Thompson, H.S. 1841. On subsoil ploughing. *J. Royal Agricultural Society of England* 2: 26-37.

Trafford, B.D. 1970. Field drainage. *J. Royal Agricultural Society of England* 131: 129-52.

Trafford, B.D. 1971 Agricultural land drainage. Welsh Soils Discussion Group Report 12: 68-84.

Trafford B.D. 1973a. The relationship between field drainage and arterial drainage - theoretical aspects. *FDEU Technical Bulletin 73/10*, MAFF, London.

Trafford, B.D. 1973b. The analysis of inflow into some experimental agricultural drains. *Hydrological Sciences Bulletin* 18: 431-40.

Trafford, B.D. 1975. Improving the design of practical field drainage. *Soil Science* 119: 334-338.

Trafford, B.D. 1977. Recent progress in field drainage: Part I. *J. Royal Agricultural Society* 138: 27-42.

Trafford, B.D. 1978. Recent progress in field drainage: Part II. *J. Royal Agricultural Society* 139: 31-42.

Trafford, B.D. 1987. A review of the UK work of the drainage and irrigation engineer. Gerald Lacey Memorial Lecture. International Commission on Irrigation and Drainage, British Section, London.

Trafford, B.D. and Rycroft, D.W. 1973. Observations on the soil water regimes in a drained clay soil. *J. Soil Science* 24: 380-91.

Truesdale, V.W. and Howe, J.M. 1977. Water level recorder and weir tank. In Newson, M.D. (ed) *I.H. Report No. 43*, Wallingford, 33-37.

USDA. 1985. *DRAINMOD User's Manual.* Soil Conservation Service, US Department of Agriculture.

Van Der Beken. 1987. The development of the theory and practice of land drainage in the nineteenth century. In Wunderlich, W.O. and Prins, J.E. (eds) *Water for the Future*. A.A. Balkema, Rotterdam 91-99.

Vassos, C. 1982. The effects of improved land drainage on river flows. Unpublished BSc Final Year Civil Engineering project, Polytechnic of North London.

Viessman, W., Harbaugh, T.E. and Knapp, J.W. 1972. *Introduction to Hydrology*. Intext Educational Publishers, New York.

Walsh, R.P.D., Hudson, R.N. and Howells, K.A. 1982. Changes in the magnitude - frequency of flooding and heavy rainfalls in the Swansea Valley since 1875. *Cambria* 9: 36-60.

Ward, R.C. 1967. Design of catchment experiments for hydrological studies. *Geographical J.* 133: 495-502.

Ward, R. C. 1971. Small watershed experiments: an appraisal of concepts and research developments. University of Hull Occasional Papers in Geography No 18.

Ward, R.C. 1978. *Floods: A Geographical Perspective.* Macmillan, London.

Ward, R.C. 1982. The Catchwater Drain experimental catchment. Department of Geography Miscellaneous Series No. 26, University of Hull.

Ward, R.C. 1984. Hypothesis-testing by modelling catchment response. *J. Hydrol.* 67: 281-305.

Ward, R.C. 1985. Hypothesis-testing by modelling catchment response II: An improved model. *J. Hydrol.* 81: 355-73.

Ward, R.C. and Robinson, M. 1990. *Principles of Hydrology.* McGraw-Hill Book Company, London and New York.

Warmerdam, P.M.M. 1982. The effect of drainage improvement on the hydrological regime of a small representative catchment area in the Netherlands. In *Application of Results from Representative and Experimental Basins.* Unesco Press, Paris 318-338.

Weisman, R.N. 1977. The effect of evapotranspiration on streamflow recession. *Hydrol. Sci. Bull.* 22: 371-377.

Weyman, D.R. 1975. *Runoff Processes and Streamflow Modelling.* Oxford University Press, London.

Whisler, F.D. and Bouwer, H. 1970. Comparison of methods for calculating vertical infiltration and drainage in soils. *J. Hydrol.* 10: 1-19.

Wijkam, A. and Timberlake, L. 1984. *Natural Disasters: Acts of God or Acts of Man?* Earthscan, London.

Wilcock, D.N. 1977. The effects of channel clearance and peat drainage on the water balance of the Glenullin basin, Co Londonderry. *Proc. Royal Irish Academy* 77B: 253-67.

Wilcock, D.N. 1979. The hydrology of a peatland catchment in N Ireland following channel clearance and land drainage. In Hollis, G.E. (ed) *Man's Impact on the Hydrological Cycle in the UK.* Geo Abstracts, Norwich 93-107.

Wilkins, R.J. 1982. The permanent grassland division at North Wyke. In the Grassland Research Institute Annual Report for 1981, Hurley 112-18.

Wilson, E.M. 1983. *Engineering Hydrology*. Macmillan, London.

Wisdom, A.S. 1976. *The Law of Rivers and Watercourses*. Shaw and Sons, London 3rd edn.

Wisler, C.O. and Brater, E.F. 1949. *Hydrology*. Chapman and Hall, London.

Withers, B. and Vipond, S. 1974. *Irrigation Design and Practice*. Batsford, London.

Wood, T.R. 1981. River management. Ch 6 in Lewin, J. (ed) *British Rivers* 170-95.

Woodward, S.M. and Nagler, F.A. 1929. Effects of the drainage on flood runoff of the Iowa and Des Moines rivers. *Trans. Am. Soc. Civil Engrs* 93: 821-39.

Youngs, E.G. 1976. Determination of the variation of hydraulic conductivity with depth in drained lands and the design of drainage installations. *Agricultural Water Management* 1: 57-66.