SOME CONSEQUENCES OF MOLE DRAINING A YELLOW-GREY EARTH UNDER PASTURE

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ABSTRACT

Although subsurface drainage of pasture soils is widely practiced in New Zealand there is little information available which details the likely benefits of such drainage schemes. As drainage is becoming increasingly expensive there is a need for more quantitative data on which to base assessments of the likely cost-effectiveness of proposed schemes.

The effect of subsurface drainage on certain soil and plant properties was investigated at a research site on a sheep and beef farm 6 km from Palmerston North. The soil type was a yellow-grey earth, with poor drainage due to water perching on the fragipan. Of nine plots, each 0.4 ha in area, three were left undrained and six were mole drained. Three of the drained plots had conventional pipe collecting drains and the other three used major mole channels as collecting drains. The research site was grazed as part of the normal farm rotation. Data were collected in 1981 prior to the installation of drains, then from 1982 to 1984.

Watertable levels were monitored in a series of four groundwater observation wells on each plot and the gravimetric water content of the top 30 mm of each plot was determined on a regular basis from soil cores. Soil temperature measurements were made at 50 mm depth on a pipe-mole and undrained plot, using thermistor thermometers, and at 100 mm depth on all the pipe-mole and undrained plots using mercury-in-glass thermometers.

Pasture growth rates were measured in caged areas using a capacitance pasture meter and by mowing. Residual pasture left by the grazing animal was determined using small quadrats, the pasture meter and by visual assessment. Botanical composition was determined by point analysis and dissection of samples removed from the caged areas. Available soil nitrogen, phosphorus and sulphur in the top 75 mm of each plot, and the total levels of these three nutrients in grass and clover grown on the plots, were measured using standard procedures. Two radioactive isotopes (^{32}P and ^{35}S) were used simultaneously to study the plant root activity on the undrained and pipe-mole plots.

Data from groundwater observation wells showed that mole drainage was very effective at lowering the watertable following heavy rain in winter or spring. There was no significant difference between watertable depth on the pipe-mole and mole-mole plots. The close proximity of the watertable to the surface on the undrained plots was reflected in high soil water content values for the top 30 mm of soil.

Differences in water content of the surface soil between drained and undrained plots did not affect the levels of extractable phosphate, sulphate, ammonium or nitrate or the pH in the top 75 mm of soil. Soil temperature measurements at 50 and 100 mm depth showed that drained plots did not warm any more quickly in spring than did undrained plots. A simple mathematical analysis confirmed that the lowering of the soil heat capacity by drainage would not be expected to affect soil temperature significantly in a yellow-grey earth under pasture.

There was little difference in pasture growth rates and utilisation during the very dry winter and spring of 1982, but during mob grazing in the wetter winter of 1983 utilisation was approximately 25% greater on drained than undrained plots. Subsequently, utilisation of pasture by sheep which were set stocked in spring continued to be poorer on the undrained plots, with approximately 35% more residual dry matter remaining on the undrained than on the drained plots. From the time of mob grazing in July until the end of spring both mowing and the pasture meter data showed that growth rates were approximately 30% greater on the drained plots.

Point analysis at the end of spring revealed that on the undrained plots there was a 3-fold increase in the incidence of weeds, a 4-fold increase in the incidence of bare ground and a 2-fold decrease in the incidence of clover compared with the drained plots. Almost identical results were obtained from herbage dissections.

There was also a decrease in the concentrations of N, P and S in the dry matter of grass and clover grown on the undrained plots compared with that grown on the drained plots. These differences were for the most part small and ephemeral.

Isotope uptake studies showed that in winter drainage enabled both grass and clover roots to extract both sulphate and phosphate from a greater depth, with approximately 6% of the relative root activity occuring at 40 - 80 mm depth on the undrained plots compared with approximately 15% on the drained plots. In spring, approximately 16% of the relative root activity was at 80 - 200 mm depth on the undrained plots compared with approximately 26% on the drained plots.

The benefits of drainage became apparent only after grazing on a wet soil and were probably due to the effect that drainage had on the water content and so strength of the surface soil. Drainage increased the bearing strength of the surface soil, minimizing treading damage to both the sward and the soil structure and therefore enhancing both pasture utilisation during grazing, and subsequent regrowth.

A simple mathematical model was developed, which used weather data to predict the watertable levels in both drained and undrained soil. By varying certain soil properties and drainage design parameters within the model, the limiting steps in the drainage process in the Tokomaru silt loam were investigated. The model was also designed to calculate the number of days over the winter-spring period on which the surface soil would be so wet that grazing would have the adverse consequences described

above. In a year of average rainfall, mole drainage reduced the number of such 'unsafe' grazing days from 69 to 10. By comparing the number of 'unsafe' grazing days for different rainfall regimes some idea of the cost-effectiveness of drainage may be ascertained.

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CHAPTER 1

CHAPTER 1

GENERAL INTRODUCTION

1.1 The Need for Research into the Effects of Drainage

It has been estimated (Fletcher, 1982) that despite an increase in subsurface drainage practices in recent years, approximately 42% (6,370,000 ha) of the arable land in New Zealand has a wetness limitation and would be likely to benefit from drainage. Poor drainage apparently imposes severe restrictions on agricultural, forestry and horticultural practices and production.

Although many farmers in New Zealand have adopted various drainage practices to alleviate wetland problems, there is little experimental data defining the benefits of these practices in terms of production. The relationship between crop growth and wet soil has been studied extensively overseas, as the review by Wesseling (1974) shows. However, much of this research is of limited applicability because of the unique climate, soils and dominantly pastoral form of agriculture in New Zealand.

Drainage of agricultural land is becoming increasingly expensive. As Tillman (1984) recently pointed out, if drainage of pasture land costs $750 per hectare, this is approximately equivalent to the expenditure on fertilizer over nearly twenty years. Yet compared to fertiliser research, funds devoted to drainage research are very meagre.

There are few quantitative data available in New Zealand which show the effects of waterlogging on pasture yield and animal performance. Nor are there data showing how successful drainage systems are in alleviating these effects. Thus, although many farmers recognise that expenditure on land drainage is a necessary part of land development, many others remain to be convinced that it is economically worthwhile. At a time when the economics of farm inputs are being examined more critically, and in view of the large area of land involved, it is important to obtain quantitative data on the effects of drainage systems on pasture. Such data can form the basis of a cost-benefit analysis when drainage is being planned.

1.2 Claimed Benefits of Drainage

A summary of the claimed benefits likely to result from the installation of subsurface drainage systems is presented by Thomas and Evans (1975). They state that the advantages of adequate drainage are:

(i) Well drained soils warm up earlier in spring providing earlier grass production.

(ii) Drained grassland can carry stock earlier and later in the year without the same risk of poaching. Poaching danger at high stocking rates is reduced.

(iii) A wider range of grasses and forage crops can be grown.

(iv) The adverse effects of drought are reduced because of the development of a more extensive root system.

(v) Deeper and more extensive rooting systems can extract nutrients from a greater volume of soil.

(vi) Soil structure is improved as the result of better root penetration, and damage to soil structure by the passage of wheeled vehicles and cultivating implements (tractors, fertilizer drills, harrows and so on) is reduced.

(vii) Mineralization of nitrogen is increased due to better aeration.

(viii) Better use can be made of irrigation because the risk of overwatering is reduced.

(ix) Well drained soils are less prone to give rise to certain animal diseases, e.g., liver fluke.

Although the above list was based on United Kingdom experience, most of the points are potentially relevant to pastoral farming in New Zealand. It is the aim of this thesis to determine whether or not there is any substance to the claimed benefits of drainage under pasture and to determine the magnitude of these benefits. A detailed review of the above factors is not presented here, but appears in the appropriate sections of the thesis.

1.3 An Overview of Drainage Techniques

As pointed out above, field drainage has received much less attention from the research worker than many other aspects of agriculture. Although various drainage practices have been widely adopted to control excessive soil wetness, particularly in Europe, the United Kingdom and parts of the United States, the techniques used have generally followed a pattern which has become traditional for the soil and farming in the particular area.

A number of reviews of land drainage techniques exist, for example those by Hudson et al. (1962) and Donnan and Schwab (1974). In addition, recent drainage research in the United Kingdom conducted by the Field Drainage Experimental Unit (FDEU) is described in annual reports and associated publications (Rycroft, 1972; Steinhardt and Trafford, 1974; Trafford, 1975). Current New Zealand drainage problems and practices have been outlined by Bowler (1980).

Land drainage methods available include surface drains (open drains, furrows, channels, bedding, grassed waterways) and subsurface drains (field pipes, combined pipe and mole, mole, subsoiling). In the past in

New Zealand large areas were drained using surface methods. Hudson et al. (1962) argue, however, that farmers have used open drains much too freely. Consideration must be given to factors such as valuable loss of ground in drain construction, cleaning and maintenance costs, farm access and stock losses especially during calving and lambing.

In contrast, carefully designed subsurface drainage systems ensure better control of surplus soil water and provide a more favourable environment for root and crop growth (Schwab et al., 1966; Williamson and Kriz, 1970; Cannell, 1979). In addition, subsurface drains do not interfere with stock or machinery movement and maintenance is limited to outfall protection and remoling, if required. The conditions where surface drainage is preferred to subsurface drainage have been listed by Bowler (1980).

The aim of all good design, regardless of drainage method, might be defined as "minimizing the cost and maximizing the benefits" (Trafford, 1975). When planning drainage systems, attention should be given to the present and future land use, the soil type and depths of soil horizons, and the cause of the wetland problem. These factors have been clearly outlined by Hudson et al. (1962) and Bowler (1980). According to Trafford (1975), the major design decisions to be considered when planning a drainage system are:

(i) General layout
(ii) Drain depth
(iii) Drain spacing
(iv) Pipe size
(v) Materials
(vi) Secondary drainage treatments.

In fine-textured soils (clays to silt loams) the hydraulic conductivity is such that even closely-spaced pipe drains are insufficient to control excessive soil water. For example, Trafford (1975) has suggested that in a heavy clay soil satisfactory drainage may be achieved by pipe spacings as close as 3 m with gravel backfill to the surface. Such expensive measures can rarely be justified on economic grounds.

Mole drainage is an inexpensive form of drainage particularly suited to fine-textured soils. Childs (1943) and Trafford and Rycroft (1973) have attributed the effectiveness of mole drains to their close spacing. A single mole drain is a channel, usually circular in cross-section and about 100 mm in diameter, formed below the land surface by drawing a torpedo-shaped cartridge through the ground. In a typical system parallel mole drains are drawn 2 m apart at a depth of about 450 mm.

The following chapters describe an investigation into the efficiency of drainage and its effect on certain soil and pasture properties. Also included is a comparison of two mole drainage treatments; pipe-mole, where the collecting drain is conventional pipe, and mole-mole where the collecting drain is a mole channel.

1.4 Objectives of this Study

At the present time the decision as to whether to drain or not is based largely on practical experience, due to the lack of precise data, as referred to above. The need exists therefore, for carefully planned drainage research to evaluate the effectiveness of subsurface drainage in relation to the removal of excess water and the reduction of pugging in winter and spring. In addition, data on pasture responses to subsurface drainage are required.

It was therefore proposed to evaluate mole drainage under grazed pasture as it affects:

(i) Certain physical properties of the soil, with an emphasis on soil water.

(ii) Pasture production and utilisation by the grazing animal.

(iii) Pasture species composition and chemical composition.

(iv) Soil nutrient status, plant root distribution and the depth of nutrient uptake.

(v) Soil temperature.

It was hoped that after monitoring the effect of drainage on the above soil and plant properties, data could be presented which would clearly quantify and explain any benefits of drainage under pasture.

Having established what (if any) the benefits of drainage were, and which properties had the greatest influence on these benefits, it was hoped that the advantages to be gained from mole drainage could be expressed in a manner which allowed the effects of mole drainage to be determined for different winter-spring weather patterns. Thus, another objective of the study was to develop a model which would help in extrapolating the results obtained in the field study to other sites, and to other years.

CHAPTER 2

CHAPTER 2

GENERAL DESCRIPTION OF THE KEEBLE FARM DRAINAGE EXPERIMENT

2.1 Introduction

The field experiment which was the focus of this study is outlined in this chapter. A brief description of the physical environment at the site is given. Then the plot layout and drainage systems are described. Finally the parameters measured are listed.

2.2 The Experimental Site

The Keeble property on which the research site is located is situated near Palmerston North at grid reference NZMS1 N149/093301, at an altitude of 60 metres. The research paddock was nearly flat and had at the commencement of this investigation a sward composed of predominately ryegrass (Lolium perenne) and white clover (Trifolium repens).

The Keeble property is a sheep and beef farm owned by Massey University. In the winter months a mob of 2700 ewes is rotationally grazed around the farm's paddocks including the research area. In late winter-early spring the research area is set stocked at a rate of 17 ewes ha^{-1} in preparation for lambing.

The average annual rainfall for Palmerston North is 995 mm, with an average winter rainfall of 280 mm and an average summer rainfall of 241 mm. A feature of the climate of the Palmerston North area is the winter and spring water surplus as illustrated in Fig. 2.1.

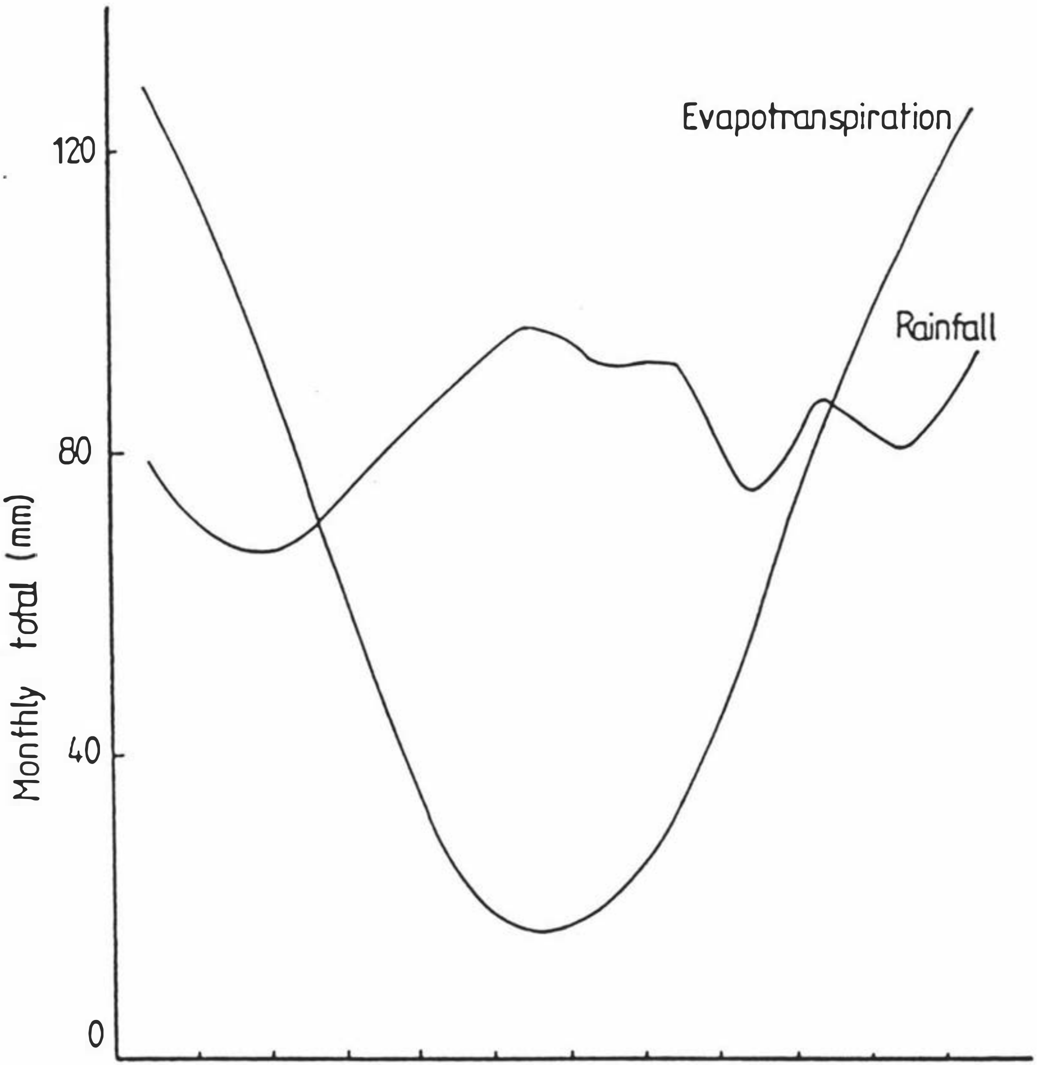


Figure 2.1 Longterm average rainfall and Penman potential evaporation for Palmerston North .

The soil type is Tokomaru silt loam, which is classified as an Aeric Fragiaqualf (Soil Survey Staff, 1975) and as a gleyed yellow-grey-earth (New Zealand Soil Bureau Staff, 1968). The soil has been described elsewhere in detail, with morphological data being presented by Pollok (1975) and physical data by Scotter et al. (1979a).

Pollok (1975) drew attention to some of the outstanding features of this profile (Appendix A). He states that the soil consists of a silt loam A horizon of medium texture, underlain by a strongly developed, heavy textured clay loam B horizon. At the research site the permeable A horizon extends down to a depth of 300 mm where the impermeable B horizon begins and extends to a depth of approximately 700 mm.

Another characteristic of this soil is the presence of a densely packed fragipan located approximately 700 mm below the soil surface. This horizon impedes the movement of percolating soil water, and consequently a perched watertable is often present under undrained conditions. This results in saturation of the topsoil for long periods during the winter and spring when rainfall usually exceeds evapotranspiratic

2.3 Plot Layout and Drainage Treatments

The research paddock was 4.6 ha in area and was divided into 9 plots as indicated in Fig. 2.2. Each plot was 80 m in length and 50 m wide, giving a plot area of 0.4 ha. The plots were separated by 10 metre wide buffer strips.

In the spring of 1982 three treatments were imposed on the area:

(i) Mole and pipe drainage: Slotted plastic 'Novaflow' pipe was installed at a depth of 700 mm, with a 40 metre spacing, and a gradient of 1%. Mole drains were pulled at a depth of about 450 mm, with 2 metre spacings, on a grade of 1.4%,

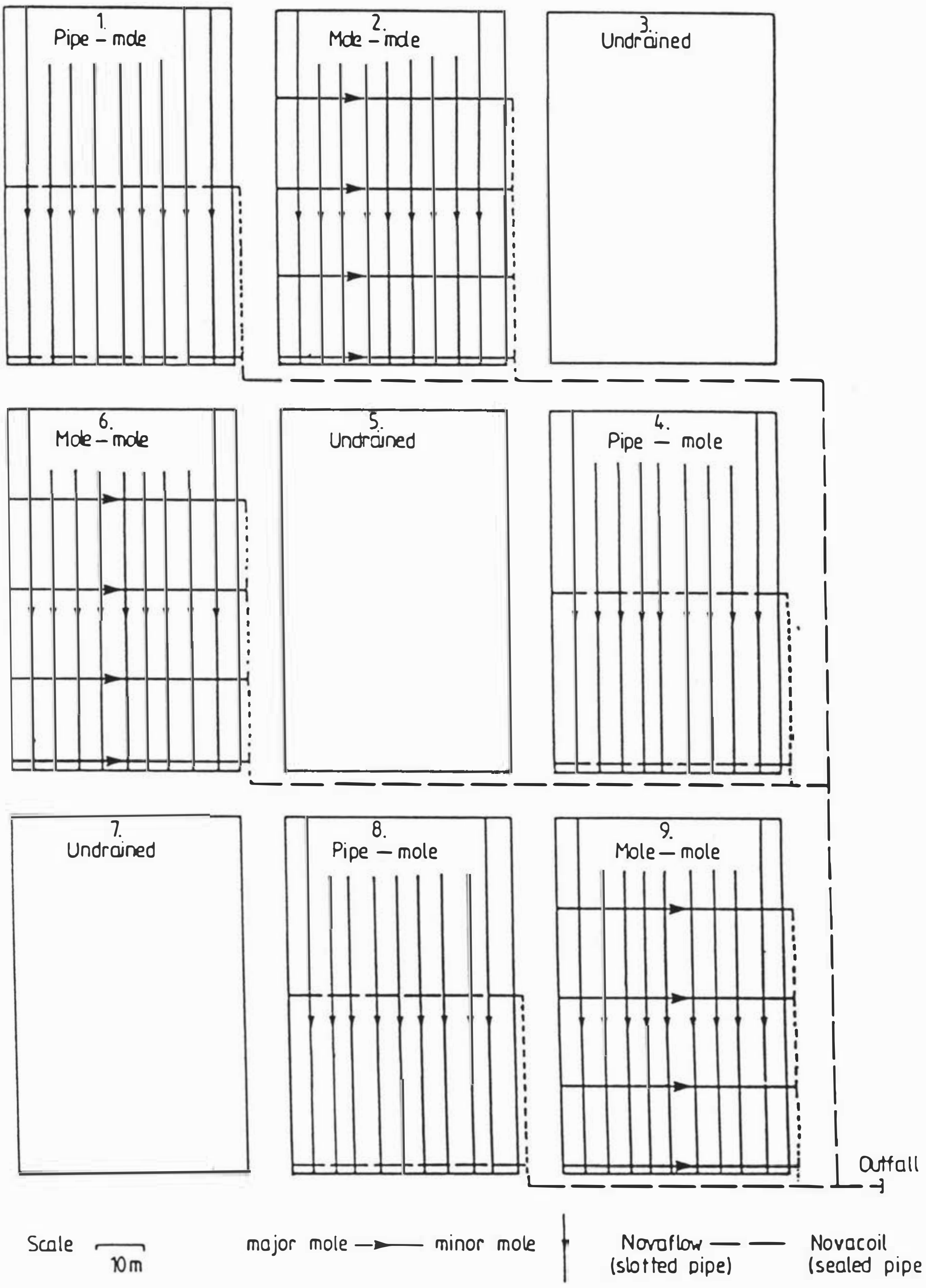


Figure 2.2 Layout of drainage research area showing Plots 1 to 9

at right angles to the pipe. The drainage water was collected in 'Novacoil", (a sealed plastic pipe) at the plot boundary and carried to major discharge drains laid on a grade of 1.4% which led, via a single pipe, to the outfall. All plastic pipes were 110 mm in diameter while the mole drains were 75 mm in diameter. Backfill above the pipe was simply the soil removed in trenching.

(ii) Mole only drainage: Mole drains were pulled at 2 metre spacing, at a depth of about 450 mm, as described for the pipe-mole treatment. Instead of conventional pipe drains, major moles, also 75 mm in diameter, were pulled at right angles to the minor moles at a grade of 1.1%. The major moles were pulled at a spacing of 20 metres and at a depth of 600 mm. They discharged into sealed plastic pipes at the plot boundary as described above. Minor moles were junctioned to major moles by spearing.

(iii) Undrained: No drainage treatment was installed.

Each treatment was replicated 3 times, once in each row and column, to give a Latin square design as depicted in Fig. 2.2. The individual plots were not fenced and the entire area was available for grazing as part of the normal farm rotation.

2.4 Parameters Measured

Intensive monitoring of certain climate, soil and plant parameters took place in the years 1981 through to 1984, inclusive. The main parameters measured were:

1) Rainfall: A continuously recording rain gauge which siphoned automatically was installed at the site, and this enabled rainfall amounts and intensities to be measured.

ii) Drainage water: At the junction where the pipe from each drained plot met the main collecting lateral, a weir was installed to measure the flow of water from the drains.

iii) Soil temperature: Soil temperatures were measured by mercury-in-glass soil thermometers placed at a depth of 100 mm and thermistor thermometers placed at 50 mm.

iv) Soil moisture and watertable depth: Soil moisture was monitored using a neutron moisture meter and by gravimetric sampling. Water table depth was measured using a grid of observation wells on each plot.

v) Pasture growth and utilization: Four techniques were used to measure pasture utilization and growth. These were cutting caged areas, cutting quadrats, visual assessment and a pasture meter.

vi) Botanical composition: Two methods were used to assess the composition of the pasture sward. These were dissections of cut samples removed from the area, and point analyses carried out on the area.

vii) Chemical analyses of both soil and pasture: Levels of nitrogen, phosphorus and sulphur in both soil and plant samples were determined using standard procedures.

viii) Plant root distribution: The activity of plant roots at different depths within the soil profile was studied using the radioactive tracers ^{32}P and ^{35}S.

Detailed descriptions of the techniques used and results obtained are given in the following chapters. A number of different statistical tests were used to test the significance of differences in parameters between treatments, as will be explained in the appropriate sections.

CHAPTER 3

CHAPTER 3

THE EFFECT OF MOLE DRAINAGE ON SOIL WATER

3.1 Introduction

In Chapter 1 the claimed benefits of drainage were listed, and these benefits will be examined critically in subsequent chapters. But the specific role of any drainage system is to remove excess water from the root zone as quickly and as cost-effectively as possible. This chapter discusses the effect of drainage on watertable levels and soil water content.

If drains are installed in fine-textured soils, such as the Tokomaru silt loam, but without moling or any alteration to the structure of the impermeable subsoil, there will be little water movement in the subsoil and so the watertable will frequently be close to the surface. Trafford and Rycroft (1973) showed that pipe-mole drainage maintains watertable levels lower than drainage with pipes alone. They found that moling improved the drainage efficiency, both in the amount of surplus water removed and in the control of the watertable at desirable levels. Mole drainage modifies drain performance by providing for the quicker disposal of water, so that the watertable is lowered and subject to much smaller fluctuations in level (Bowler, 1980).

As a consequence of lowering the watertable, drainage also affects the soil water content. Differences in water content between drained and undrained sites are generally largest close to the soil surface (Beven, 1980).

When carried out under favourable conditions, moling is a soil treatment which initiates the development of improved soil structure

(Scotter et al., 1979a: Leeds-Harrison et al., 1982). In a moling experiment on a clay soil, Rycroft (1972) showed that above the mole channels the effective conductivity was 4100 mm d^{-1} while in a plot without this secondary treatment the maximum effective conductivity was only 260 mm day^{-1}.

Little attention has been paid to the detailed form of the outflow hydrograph of mole drainage systems, and as a result systematic analyses of land-drainage storm hydrographs are rare. The work of Childs (1943), Beven (1980) and Reid and Parkinson (1984) are the exceptions.

Childs (1943) studied the hydrographs for a mole-drained field over a number of years and demonstrated the rapid manner in which excess water is removed. Most workers have noted that flow in the drains is a function of the water balance of the soil, the quantity of rainfall and the permeability of the soil, particularly the permeability around the mole channel.

The mode of action of mole drains has also received little critical attention. Nicholson (1948) states that mole channels work by opening up and fissuring the sub-soil and thus providing pathways for water movement to the mole. This fissuring is said to be caused by the mole plough blade. Recent work (Goss et al., 1983) also states that the principal route of water from the soil to the mole drain was not uniformly through the subsoil but was via large fissures formed by the mole plough blade. Leeds-Harrison et al. (1982) showed that drain flow was much more rapid when mole channels were pulled using a mole plough than when they were formed by hydraulically jacking an expander horizontally through the soil. They concluded that the fissures fill and empty at low tensions and provide a direct route of water flow to the mole channel which results in the rapid removal of water from the upper soil layers.

It is unlikely that the actual crack left by the blade will persist over many seasons. However, dye studies in the field have pointed to preferential pathways for water movement directly above the mole along grass root and worm channels. Scotter and Kanchanasut (1981) observed that some dye-stained worm channels extended from the surface to mole depth and grass roots have been observed to ramify through the soil to beyond mole depth. It appears that the disturbance caused by the mole blade allows roots, humus and earthworms to penetrate the B horizon above the moles, and it is these factors, coupled with a tendency for drying cracks to occur where the blade has been, which permanently enhances the conductivity of the B horizon above the mole.

An understanding of the mechanisms by which the mole channel drains farm land is important so that improvements to the design of drainage systems may be made. As a first step to improving the efficiency of mole drainage, the major constraint in the system needs to be determined; that is the step of most resistance in the movement of water from the soil surface to the outfall. Possible limiting steps are:

(i) Water flow through the soil towards the mole.

(ii) Water flow around and into the mole itself.

(iii) Water flow down the mole channel.

(iv) Water flow from the mole to the collecting pipe or mole.

(v) Water flow down the pipe to the outfall.

In this chapter, the effects of mole drainage on watertable levels and soil water content in a dry year and in a normal year are examined. Analyses of watertable and drain flow data allow a discussion of the rate limiting steps in the drainage process in soils such as the Tokomaru silt loam, and the implications of this for drainage system design.

3.2 Materials and Methods

3.2.1 Watertable levels

On each of the plots, four perforated aluminium groundwater observation wells 50 mm in diameter were installed, each well being 450 mm deep. On the undrained plots, these wells were placed equidistant from one another as illustrated in Fig. 3.1. On each of the drained plots, two observation wells were installed close to a mole channel (approximately 150 mm from the mole), while the other two wells were placed midway between mole channels so that they were 1000 mm from each mole. Watertable levels were measured using a dip stick to which were fixed two wires, an oscillator and a speaker. When the wires reached the water level in the tube the electric circuit was completed and this caused an audible sound in the speaker. The water level could then be read from graduations marked on the dip stick.

3.2.2 Water content of the soil

Water content was measured using a neutron moisture meter and gravimetric sampling. The neutron moisture meter was calibrated by gravimetric sampling adjacent to the access tube. The positions of the access tubes are depicted in Fig. 3.1. The meter was used to measure the volumetric water content at 100 mm intervals from a depth of 200 mm to a depth of 1200 mm. The volumetric water content at 100 mm was determined gravimetrically in the laboratory from cores removed from the profile near the access tubes and the bulk density. The water content of the top 30 mm of the soil profile was also determined gravimetrically from 20 bulked cores removed from each plot with the assistance of a soil corer.

3.2.3 Drainage from the plots

Flow data were obtained by v-notch weirs installed at the corner of

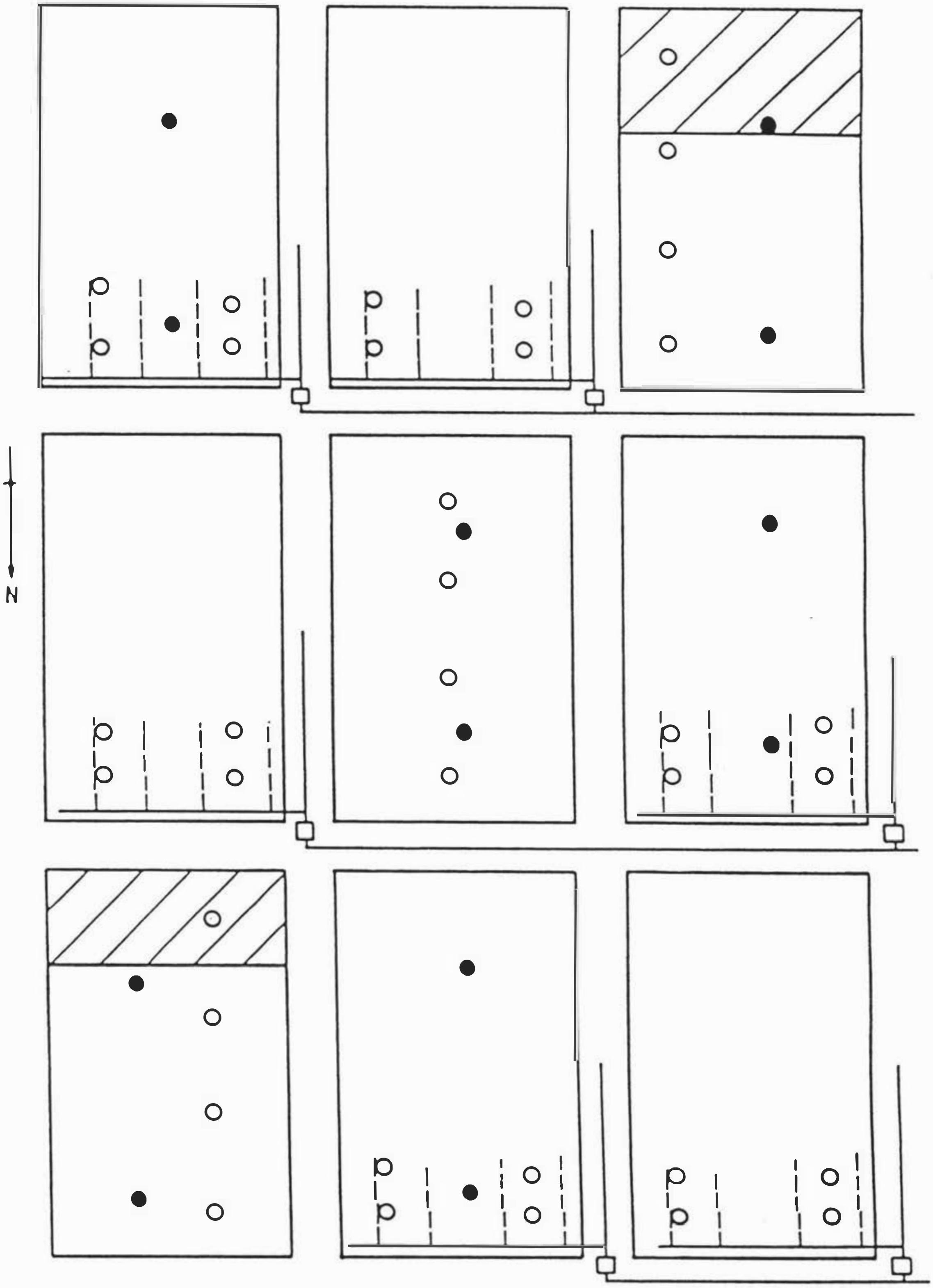


Figure 3.1 Diagram showing the location of groundwater observation wells (○) relative to mole channels (— —), the elevated portions of the undrained Plots 3 and 7 (▨), neutron moisture meter access tubes (●) and weirs (□).

each of the drained plots, as depicted in Fig. 3.1. The weirs were housed in pits, dug where the pipe collecting drainage water from the plot met the main collecting lateral. Stevens recorders were used to monitor flow through the weirs. A recorder and weir are depicted in Fig. 3.2. The weirs were calibrated over a range of flow rates using a stop watch and measuring cyclinder.

3.2.4 Statistical analysis

In most instances the statistical significance of differences between treatments was established using an analysis of variance based on a split-plot design. The use of such a design to analyse a series of successive observations on differently treated plots is sometimes referred to as a split-plot in time (Little and Hills, 1972). Least significant differences were then calculated for $P \leqslant 0.05$ and where applicable $P \leqslant 0.01$.

The statistical significance of differences between drained and pipe-mole plots in mean values for the volumetric water content for certain depths, as determined using the neutron moisture meter, were assessed using a simple t-test.

3.3 Results and Discussion

3.3.1 Effect of drainage on the watertable level

3.3.1.1 1982 - a dry year.

1982 was a very dry year with a small autumn rainfall total beginning a trend which continued on until the end of spring. Fig. 3.3 displays the rainfall for the winter-spring period of 1982. The total rainfall for the autumn period (March to May) was 173 mm which falls in the 10-20 percentile. This was followed by a winter (June to August)

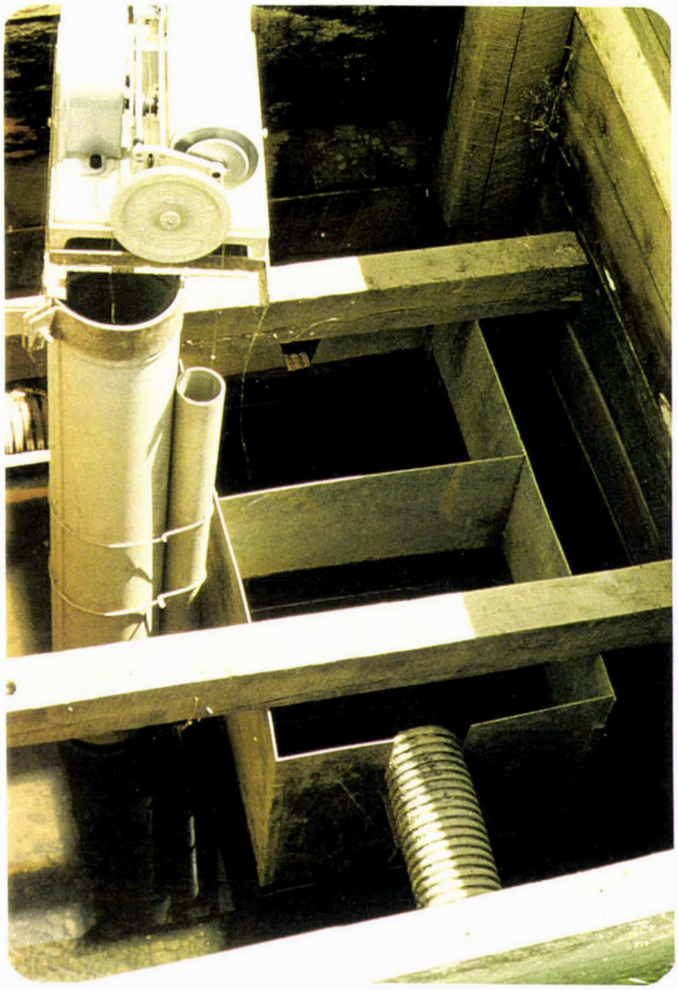


Figure 3.2 View of V-notch weir and Stevens recorder.

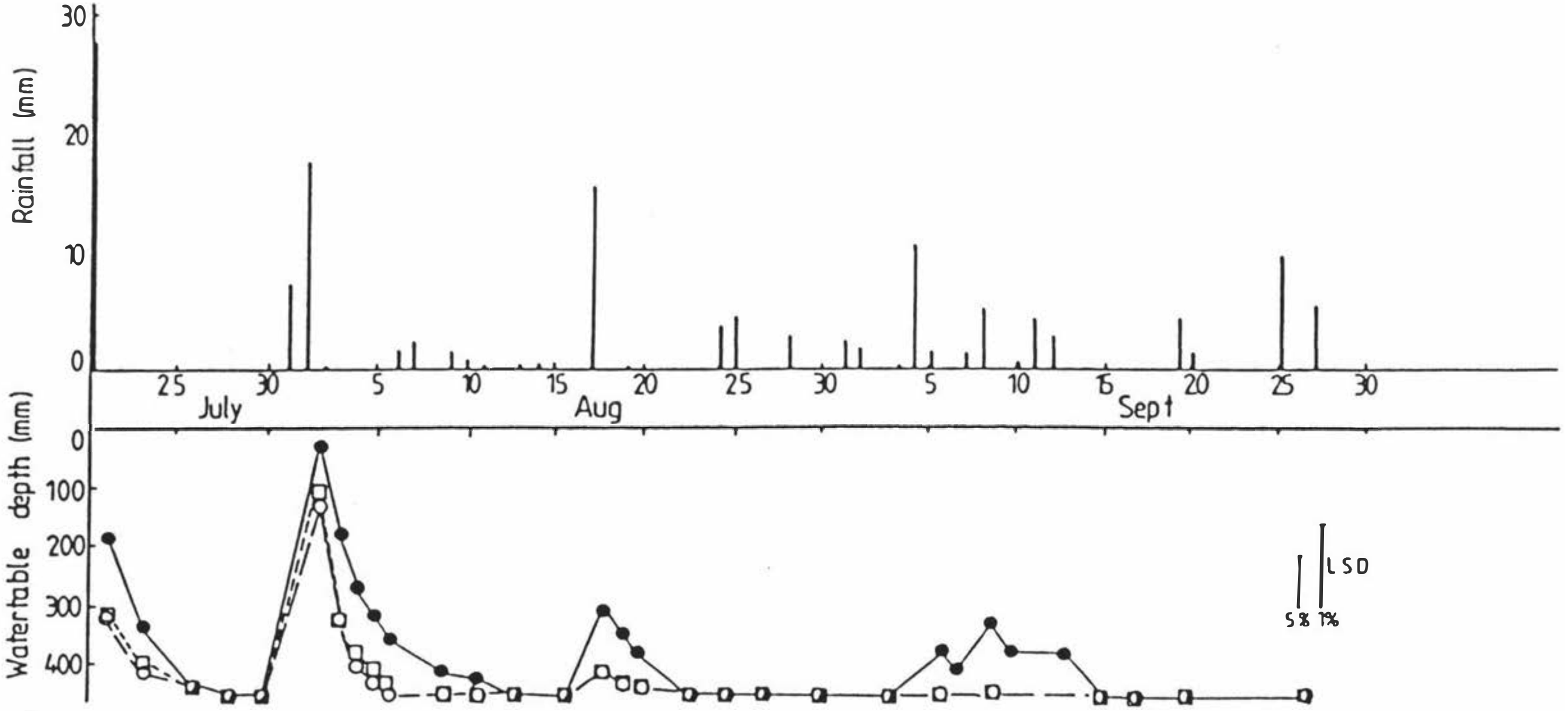


Figure 3.3 Rainfall and watertable levels as measured for pipe-mole (○--○), mole-mole (□··□) and undrained (●—●) plots in the year 1982. If the watertable was deeper than 450 mm it was assigned a value of 450 mm. Least significant difference (LSD) at the 1% and 5% level .

total of 181 mm which falls in the same percentile. The total rainfall for the spring months (September to November) of 190 mm was also low compared with other years and was in the 20-30 percentile.

Fig. 3.3 also shows the watertable levels measured during the winter-spring period of 1982. Even in a dry year, drainage has some effect, albeit small, on the watertable level, as the watertable declines more rapidly on the drained plots than on the undrained plots. However, on very few days was the watertable close to the soil surface on the undrained plots, and so the benefits of drainage are likely to be minimal in such dry years.

3.3.1.2 1983 - an average year

The rainfall measured on the research site for the winter period was 191 mm, a relatively low total, registering in the 10-20 percentile. The spring total of 229 mm was about average, falling in the 40-50 percentile. Fig. 3.4 displays the measured fluctuations in watertable levels on both drained and undrained plots, and also the daily rainfall totals. Standard deviations for watertable depths were typically about 30 mm on the undrained plot and, following rainfall, as high as 80 mm on the drained plot. The reason for this high variability in the drained plots was due largely to the positioning of the tubes, as will be explained in Section 3.3.3.

The variability on the undrained plots was probably due to differences in the micro-topography of the area, with the surface water frequently observed on the undrained areas either accumulating in low areas within the plot or else running off the slightly elevated portions of the plot onto the buffer zones surrounding the plot. Such differences are to be expected as it is unlikely that any area of land is sufficiently flat to give uniform watertable levels. The variability in watertable

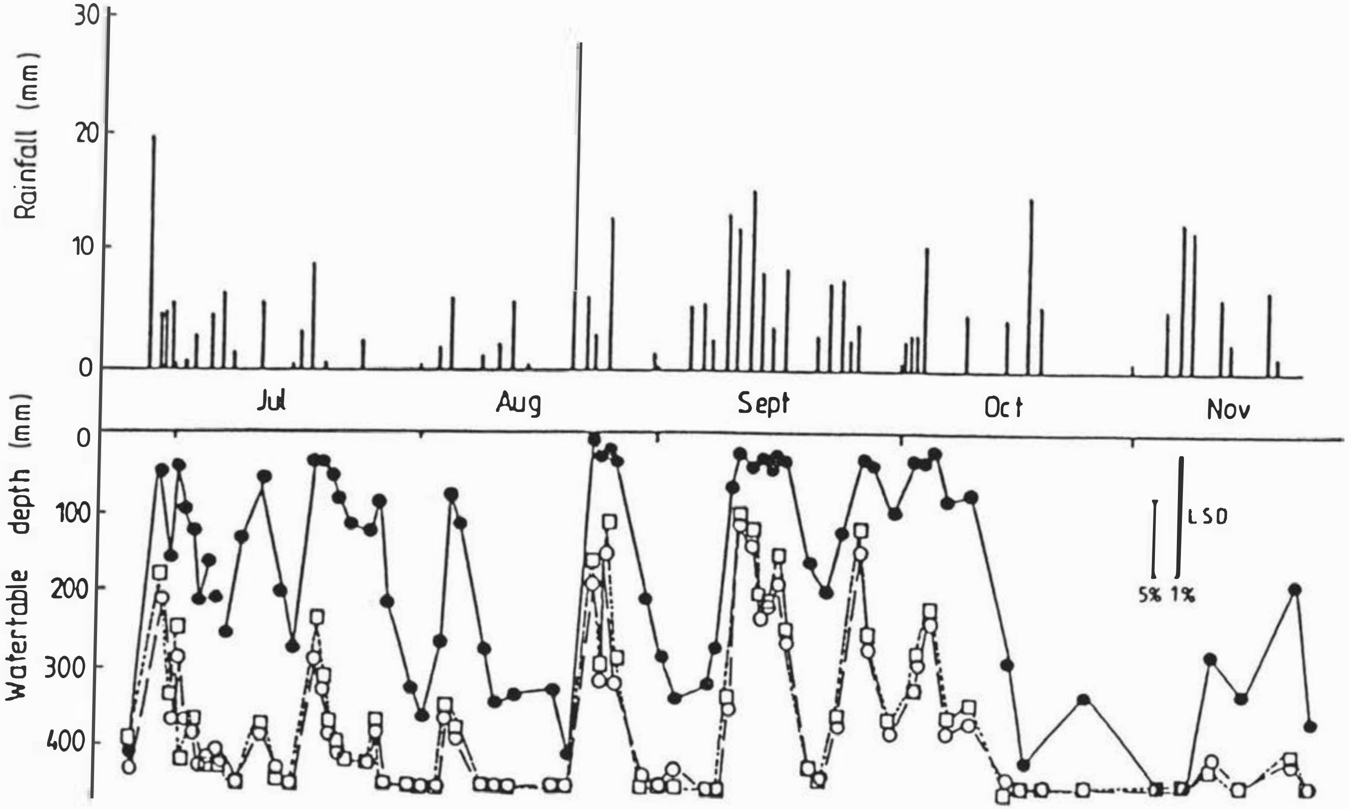


Figure 3.4 Rainfall and watertable levels as measured for pipe-mole (O--O), mole-mole (□····□) and undrained (●——●) plots in the year 1983. If the watertable was deeper than 450 mm it was assigned a value of 450 mm. Least significant difference (LSD) at the 1% and 5% level .

levels within the undrained plots was largely due to some lower values observed on certain confined areas, illustrated in Fig. 3.1. Also, it was small compared with the large difference in watertable levels between the drained and undrained plots. On Plot 7, only the top one quarter of the plot had a different watertable level to the rest of the plot, while on Plot 5 the watertable was quite uniform in behaviour. The top one-third of Plot 3 was elevated above the rest of the research paddock, resulting in lower watertable values than might otherwise be expected for an undrained plot. To differentiate between these areas, pegs were driven into the soil to mark the perimeters of the area with the lower watertable level and this area was designated 'dry'. The area outside the pegs was designated 'wet', and this constituted 80% of the undrained plot area.

The watertable rose up the soil profile following rainfall and then declined with the excess water leaving the undrained plots slowly, whereas for the drained plots, the watertable level dropped very rapidly. Differences in watertable levels between mole drained and undrained soil were also measured by Harris (1984). The internal drainage problem in Tokomaru silt loam is clearly illustrated in Fig. 3.4, with significantly (often at $P \leqslant 0.01$) higher watertable levels on the undrained plots throughout winter and spring. It is apparent, that due to the impermeable subsoil, very little deep drainage can occur. The relative importance of deep drainage and evapotranspiration in removing excess water from the undrained plots will be discussed in Chapter 7.

From the difference between watertable levels on the drained and undrained plots shown in Fig. 3.4, it can be concluded, that for a year of average rainfall the effect of drainage on watertable levels is very pronounced. For such years, mole drainage is an effective way of lowering the watertable .

3.3.2 Comparison of the performance of pipe-mole and mole-mole drainage systems

Measurements in observation wells showed that there was very little difference between the watertable levels in soil drained by moles in conjunction with collecting pipes and soil drained by a major-minor mole network. Further evidence of the similarity in performance of the two drainage treatments is found by considering the flow data as measured by v-notch weirs.

Although v-notch weirs were installed to continuously monitor the quantity of drainage water from each of the drained plots, following heavy rain the pits housing these weirs flooded so that the weirs were rendered inoperable, and peak flow data were lost. It was possible however, to record smaller flow events and the decay curves following larger flows.

Charts from the weirs showed little difference between the hydrographs for the pipe-mole and mole-mole treatments. Typical examples of these hydrographs are shown in Fig. 3.5. The response time (i.e., the time between the start of rainfall and the commencement of drainage) was the same for both treatments and the volume of water which drained from the plots was also approximately equal.

A series of decay curves for the two drainage treatments is presented in Fig. 3.6. It is noted that the curves almost coincide, suggesting little difference in the rate at which water leaves the different plots after flow has peaked.

In spite of the pits flooding and the subsequent lack of information concerning the magnitude of peak flows, it was possible to estimate from the charts the time of peak flow. Table 3.1 shows the response time for the two different drainage treatments, listing both the time flow began in the drain following rainfall and the time this flow peaked or the pits flooded. There was little difference in the response time between the

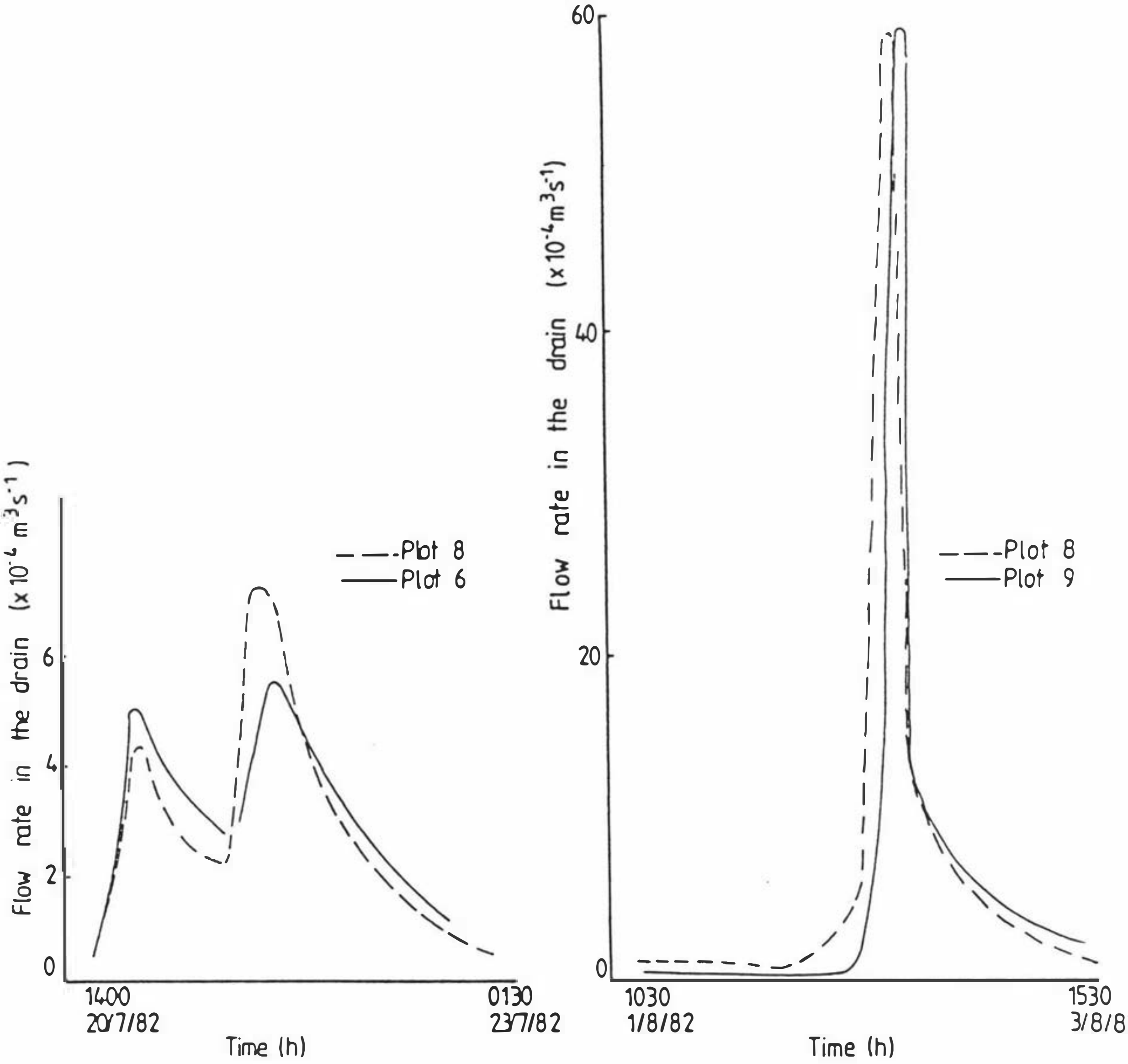


Figure 3.5 Hydrographs showing similarity in performance of pipe-mole (— —) and mole-mole (——) treatments .

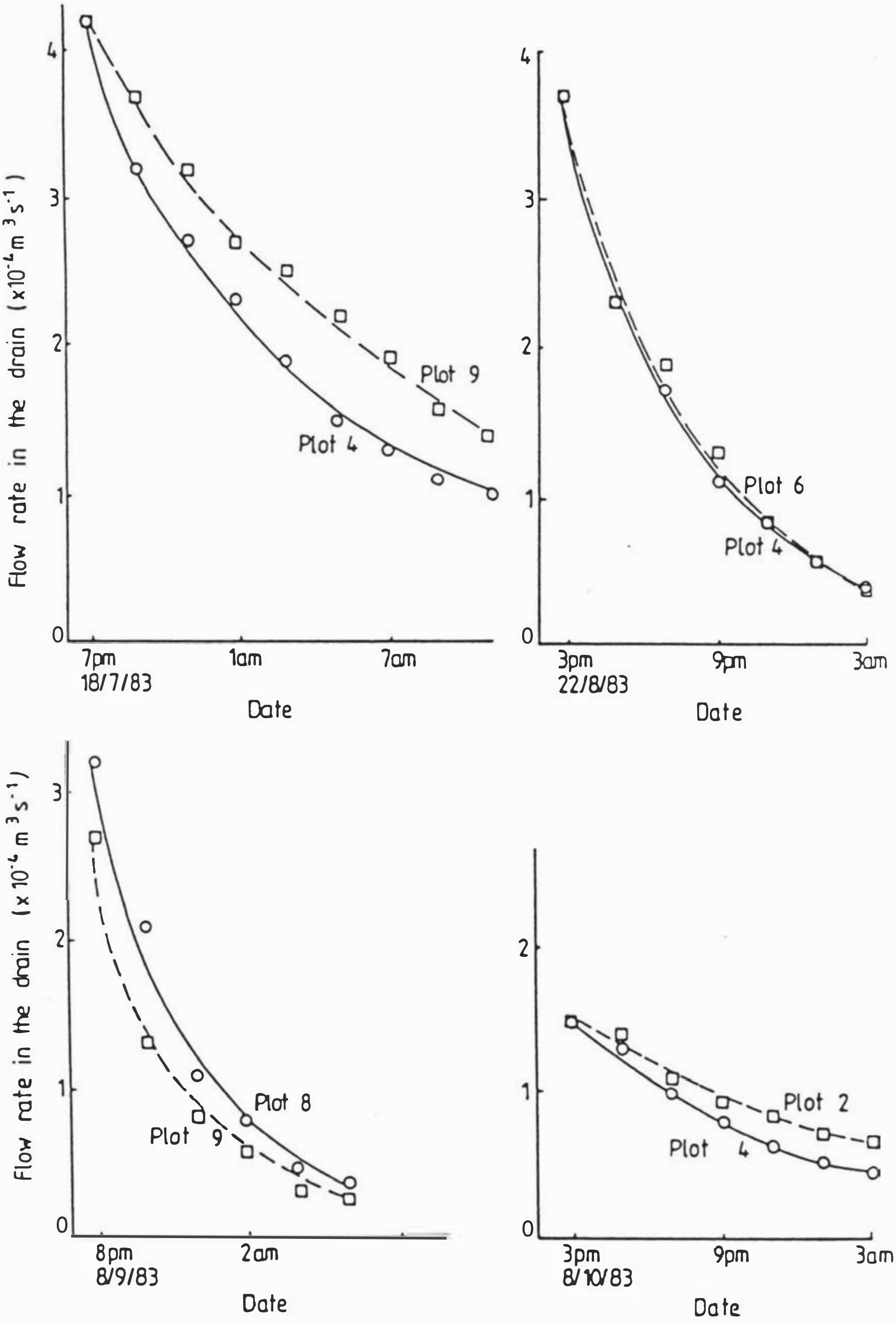


Figure 3.6 Decay curves following peak flow for pipe-mole (○—○) and mole-mole (□--□) plots .

Table 3.1 Response times for the pipe-mole and mole-mole drainage systems in 1983 (i.e. the times flow began after rainfall and the times flow peaked).

Time and amount of rainfall			Time of flow in drains					
			Pipe-mole			Mole-mole		
Date in 1983	Time	Rainfall (mm)	Plot	Start of flow	Time of peak	Plot	Start of flow	Time of peak
27/6	4pm-10pm	15.1	4	7pm	10pm	6	7pm	10pm
			8	7pm	10pm	9	7pm	10pm
18/7	10am- 2pm	9.3	4	11am	3pm	2	12am	4pm
			8	12am	4pm	6	12am	4pm
						9	12am	4pm
4/8	1am- 2pm	2.0	4	5pm	2am	2	5pm	2am
	6pm-12pm	5.7	8	5pm	2am	6	5pm	2am
						9	5pm	2am
22/8	7pm (21/8)	27.8	1	4am	6am	2	4am	6am
	-8am (22/8)		4	4am	6am	6	4am	5am
			8	3am	5am	9	4am	6am
8/9	9am-12am	5.0	1	9pm	10pm	2	8pm	10pm
	9pm-10pm	5.4	4	8pm	10pm	6	9pm	11pm
			8	8pm	10pm	9	8pm	9pm
9/9	12am- 1pm	5.6	1	12am	1pm	2	12am	1pm
			4	12am	1pm	6	12am	2pm
			8	12am	2pm	9	12am	2pm
10/9	5am- 9am	12.1	1	6am	7am	2	6am	7am
			4	6am	7am	6	5am	6am
			8	6am	7am	9	6am	7am

pipe-mole drainage treatment and the mole-mole treatment. Table 3.2 gives some examples of the volume of water that flowed through the weirs for the twelve hour period immediately after flow began in the drain. It shows that there was very little difference in the volume of water that drained from the plots with different drainage treatments.

Despite the consistency of the individual response times for individual flow events across all of the plots it is not practical to propose a mean response time. A wide range of values was observed for different events, depending primarily upon both antecedent moisture content and the intensity of rainfall, as was also found by Reid and Parkinson (1984). The first entry of Table 3.1 for early winter flow in the drain shows that the flow did not peak until approximately six hours after rainfall commenced, as opposed to events in August where flow in the drain peaked shortly after the beginning of rainfall. For early winter flows, the rapid conduction of a fraction of the rain water down the cracks brings about a comparatively quick initial outflow response, but the movement of the greater mass of water through the soil is retarded by absorptive losses to the dry soil matrix, so that peak flows are somewhat delayed.

The cracks associated with mole channels, resulting from summer drying, can allow flow to occur following heavy rainfall in early winter, even though the soil is still relatively dry. These early winter flows from drained soil help ensure a lower watertable than for undrained soil during later winter storms. Subsurface drainage acts to maintain this advantage throughout the winter-spring period, by keeping the watertable level lower on the drained soil than on the undrained soil.

Turner et al., (1976) reporting on the monitoring of flows from a 12 ha site on the same soil, found similar results to those presented in this study. They showed that the discharge increased from 40 percent

Table 3.2 Volume of water (m^3) that flowed through the weirs during the first 12 hours after the commencement of flow.

Date in 1983 Plot	27/6 7pm → 28/6 7am	28/6 9am → 9pm	30/6 6am → 6pm	9/7 8pm → 10/7 8am	10/7 9am → 9pm	16/7 4am → 4pm	18/7 12am → 12pm	3/8 5pm → 4/8 5am	8/9 9pm → 9/9 9am	21/9 12pm → 12am	1/10 9.30am → 9.30pm	21/11 2.30pm → 2.30am
4 pipe-mole	29	19	13	3	11	1	44	2	12	9	7	20
8 "	18	17	14	4	11	1	47	9	13	-	-	-
2 mole-mole	-	-	-	8	15	2	45	9	11	7	6	15
6 "	23	22	14	4	10	-	-	9	10	8	8	16
9 "	19	19	14	5	11	2	43	8				

— No measurement made.

of incident rainfall in early June to a maximum of 82 percent for a mid-season event. This increase in discharge from incident rainfall reflects changes in soil water storage as the wet season progresses.

If neither the pipe-mole or the mole-mole treatment drains more water in total, or at a faster rate, then their watertable levels will be approximately equal, as was the case for the year 1983. The conclusion to be drawn from these data is that two years after installation both treatments were draining plots in an identical manner.

An important criticism of major-minor mole networks is that after a few years it is quite likely that a major mole will collapse and cease to function properly. The minor moles would then be unable to discharge and large areas would remain waterlogged. No comment concerning the life expectancy of either drainage treatment can be made here, as this study was not of a sufficiently long duration to draw any such conclusions. All that can be stated is that for the two years of this study there did not appear to be a breakdown in either drainage treatment and that they were almost identical in performance.

3.3.3 Comparison of the watertable level close to the mole with the level midway between moles

As mentioned in Section 3.2.1, four ground water observation wells were installed on each of the drained plots, two tubes being positioned adjacent to the mole channel and two midway between mole channels. When the watertable levels measured in all the wells on a particular drainage treatment in 1983 were averaged, then the values depicted in Fig. 3.4 were obtained. If the observation wells close to the mole were considered separately from those midway between the mole, then the data presented in Fig. 3.7 were obtained.

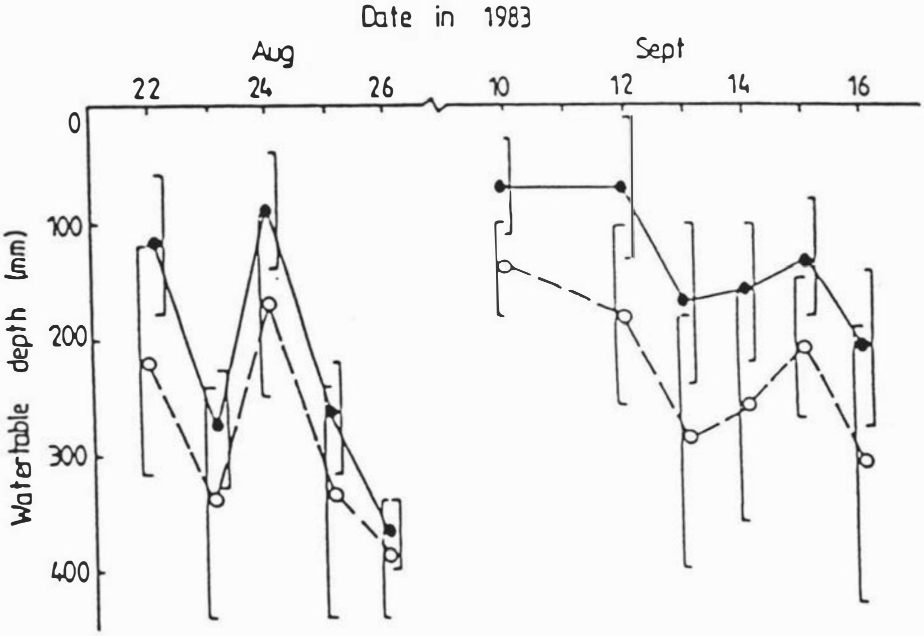


Figure 3.7 Comparison of watertable levels adjacent to the mol (●—●) with levels mid mole ○--○). Mean values a standard deviations shown are for the tubes on all the drained plots .

The watertable level measured in the observation wells next to the mole was generally lower than the level in the wells midway between mole channels. This difference was most pronounced following heavy rain when the watertable was close to the surface. However, the standard deviations of the mean values drawn in Fig. 3.7 are quite large, indicating a high degree of variability in the measured watertable levels. This variability between tubes can be explained by considering the methods used to install the observation wells. The tubes on Plots 1, 2, 4 and 6 were installed in a careful but slow manner using a hand auger. It was thought that to improve the speed of installation, use of a power auger to drill the wells in the densely packed Tokomaru silt loam, would be of great assistance. In retrospect, this was an unwise choice, as some of the tubes installed on Plots 8 and 9 using this method performed in a different manner to the other tubes. It would appear that they did not allow water to leave the aluminium tube as quickly as the other tubes, giving erroneous readings for the watertable level.

A simple experiment was carried out to determine whether or not the water level in the tubes adjacent to the mole on Plots 8 and 9 was in fact declining in a much slower manner than the level in tubes on the other drained plots. The experiment was conducted in July 1984, two days after heavy rain, when the watertable in all tubes was well below the surface and drain flow had effectively ceased but the soil profile was still moist. Water was poured down all aluminium tubes adjacent to mole channels to bring the water level in the tubes back to the surface. On Plots 1, 2, 4 and 6, water was able to leave the tubes very rapidly and after 4 hours the level was below 450 mm depth. On Plots 8 and 9, in most of the tubes after the 4 hour period the water level had only dropped about 200 mm.

A comparison is made in Fig. 3.8 between watertable levels measured midway between mole channels and those levels measured next to the mole on Plots 1, 2, 4 and 6. There is a significant ($P \leqslant 0.05$) difference between the watertable level close to the mole channel compared with that midway between mole channels. This suggests that for most of the time the major limiting factor in the drainage process in Tokomaru silt loam is the rate of water movement through the soil towards the mole channel, rather than any restriction imposed on the water entering the moles or by the carrying capacity of the moles or pipes. For a short period of time, following heavy rainfall, the flooding of the weir pits indicated that the pipes were flowing at maximum capacity. But after a few hours the rate of flow in the pipes fell rapidly. This difference in watertable levels for positions close to the mole and midway between moles, along with what it implies about water movement in the Tokomaru silt loam, will be discussed further in Chapters 7 and 8.

3.3.4 Effect of drainage on soil water content

3.3.4.1 1982 - a dry year.

In a dry year, the difference in the water content of the top 30 mm of the profile between drained and undrained was relatively small and ephemeral. Gravimetric water contents measured in the top 30 mm of the soil profile for 1982 are shown in Fig. 3.9.

Like the gravimetric data, the neutron moisture meter data shows that in a dry year drainage has little effect on the water content near the soil surface. The volumetric water content profiles, as determined on two days in August using the neutron moisture meter, are shown in Fig. 3.10. The water content near the top of the drained soil profile was not significantly different to that of the undrained soil. However below a depth of 200 mm the undrained plots were significantly ($P \leqslant 0.05$) wetter

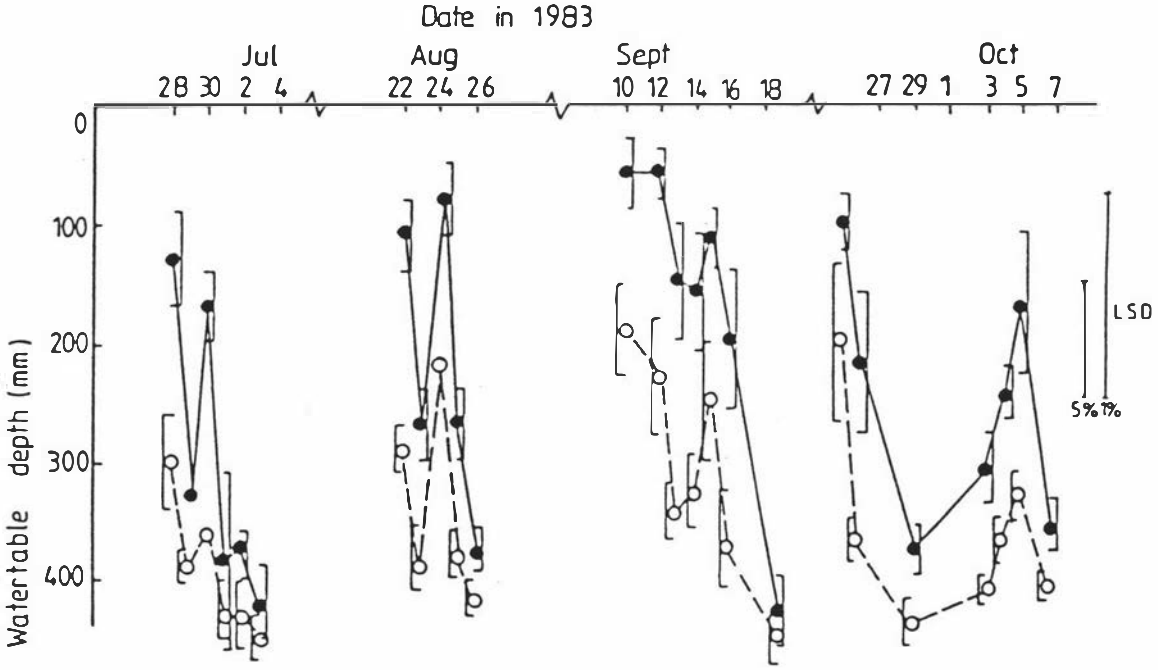


Figure 3.8 Comparison of watertable levels adjacent to the mole (●—●) with levels mid mole (○--○). Mean values and standard deviations shown are for the tubes on Plots 1, 2, 4 and 6. Least significant difference (LSD) at the 1% and 5% level .

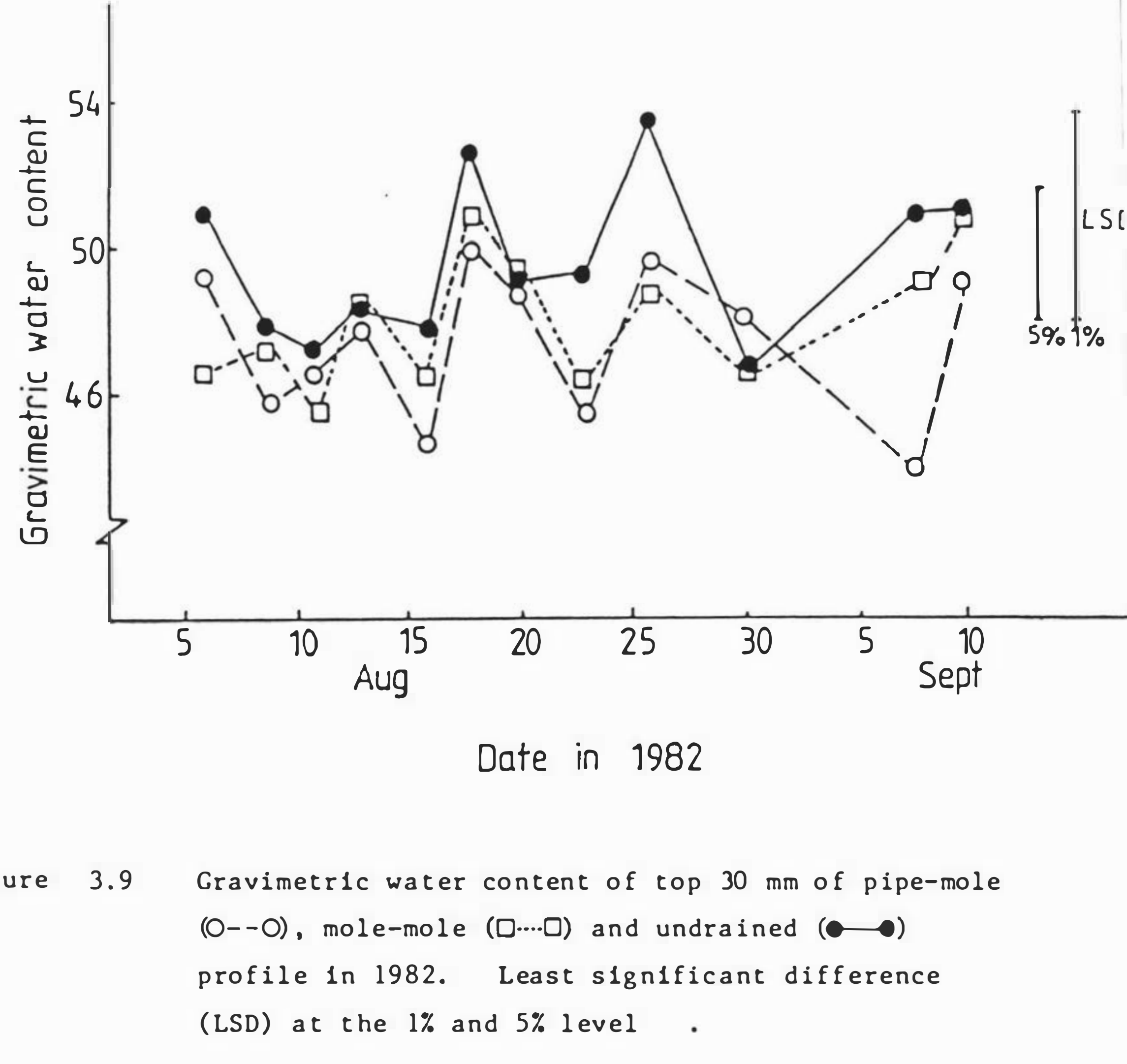


Figure 3.9 Gravimetric water content of top 30 mm of pipe-mole (○--○), mole-mole (□····□) and undrained (●—●) profile in 1982. Least significant difference (LSD) at the 1% and 5% level .

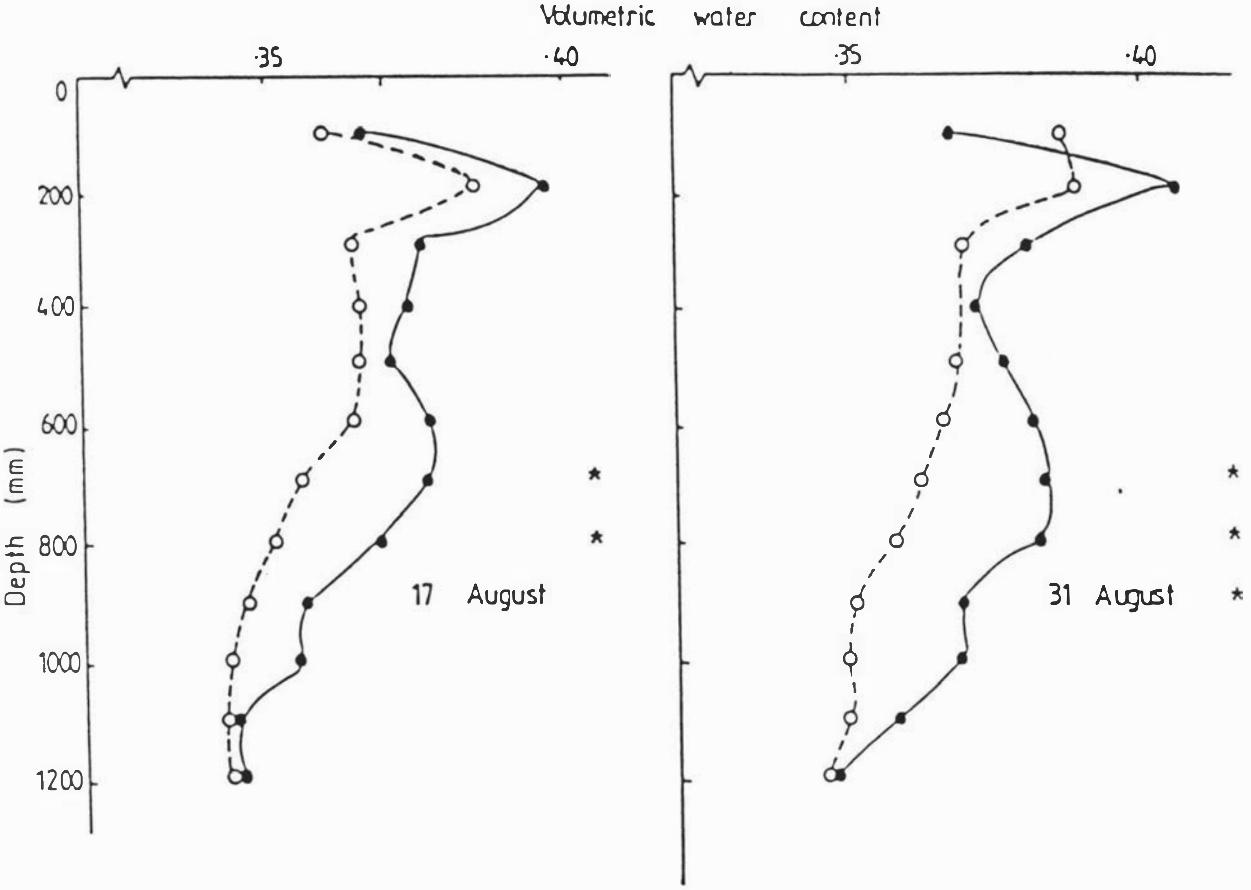


Figure 3.10 Volumetric water content of pipe-mole (O--O) and undrained (●—●) profile on two occasions in 1982. For depths where a (*) appears the difference between the mean values for the drained and undrained plots was significant at $P \leq 0.05$.

than the drained plots and surprisingly this difference continued below the moling depth down to a level of approximately 1.1 m. This suggests that the soil profile did not thoroughly rewet over the winter of 1982. The drained plots had less water in their profile because some of the water entering the plot flowed down the recently pulled mole blade cracks and mole channels which had been opened by summer shrinkage. As less water was left in the drained profile, there was less to redistribute and rewet the lower parts of the soil profile, so that the drained plots did not get as wet at depth as the undrained plots. There would therefore have been a little less water (12 mm) in the drained profile for plant use.

3.3.4.2 1983 - an average year.

Gravimetric sampling showed that in an average year, from the end of June to early October, the top 30 mm of soil was consistently wetter on the undrained than on the drained plots, averaging 0.64 compared with 0.57. The data are shown in Fig. 3.11. The similarity between the water content of the surface soil measured for the pipe-mole and mole-mole treatments serves to emphasize the points made above in Section 3.3.2 concerning the similarity in performance of these two drainage systems.

Though there was no difference in the water content of the soil at the top of the profile for the two drainage treatments, there was a significant (often at $P \leq 0.01$) difference between the undrained and drained plots. This is to be expected in light of the data presented in Fig. 3.4 which show that the watertable was nearly always closer to the soil surface on the undrained plots than it was on the drained plots. The difference in soil water content between drained and undrained soil was greatest in the spring month of September. As this is a time of good pasture growth and moderate stocking rates, the importance of lowering the

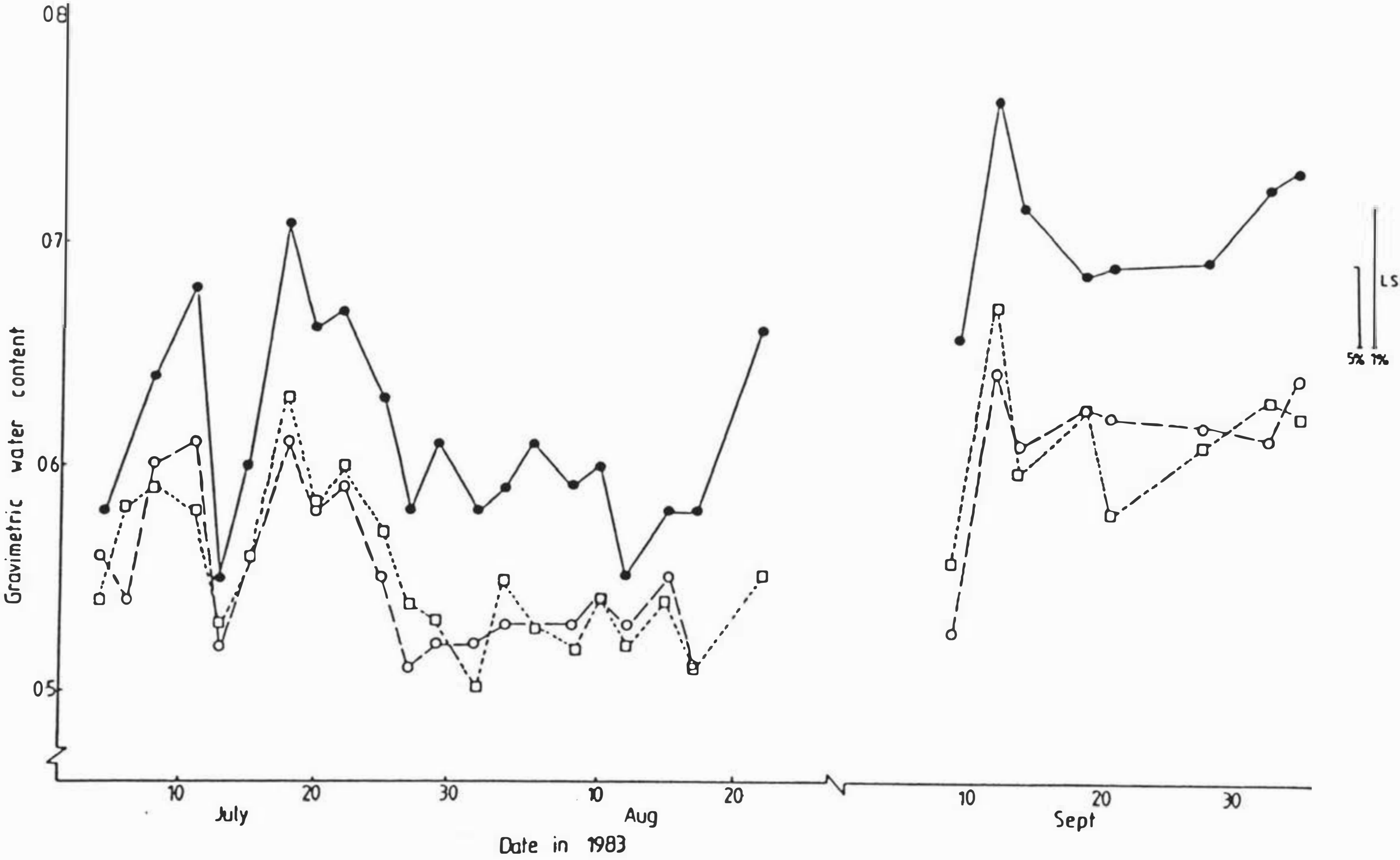


Figure 3.11 Gravimetric water content of top 30 mm of pipe-mole (O--O), mole-mole (□····□) and undrained (●—●) profile in 1983. Least significant difference (LSD) at the

soil water content by drainage takes on special significance, as will become apparent in later sections.

Neutron moisture meter data gathered in 1983 also show that drainage was effective in lowering the water content of the soil profile. Data recorded on two days in August are presented in Fig. 3.12. A feature of these data, which were typical of the data gathered over the winter-spring period, is the significant (often at $P \leqslant 0.05$) difference in the volumetric water content of the drained soil compared with the undrained soil in the 0–400 mm zone. There was approximately 16 mm more water in the undrained profile. In contrast with the 1982 data, in August 1983 there was no significant difference in volumetric water content between the drained and undrained profile below the mole channel depth. Consideration of rainfall and evapotranspiration for autumn and early winter of 1983 shows sufficient excess rain fell to recharge fully the soil profile by late July.

3.4 Conclusions

The following conclusions may be drawn:

i) In a year of average rainfall, it is important to lower the water-table level in a soil with an internal drainage problem, otherwise the soil profile remains waterlogged for many winter-spring days. Mole drainage is an effective means by which to lower the water-table in a yellow-grey earth soil.

ii) In a year when rainfall is well below average, the watertable rarely approaches the soil surface and so artificial drainage is not needed. The benefits of drainage in such years would be minimal. If mole drains are operating efficiently, drainage may decrease slightly soil water storage and be a disadvantage in a dry summer following a dry winter.

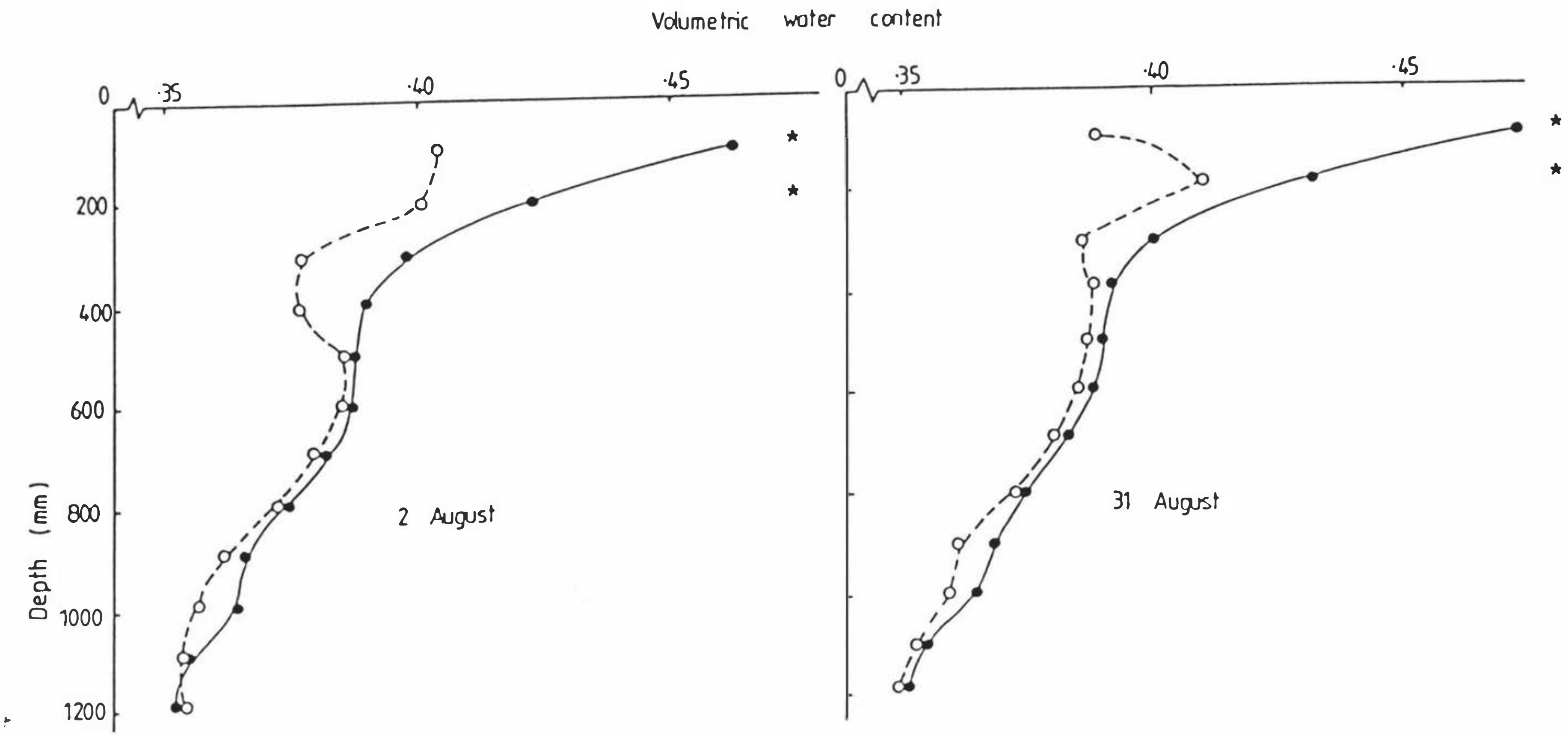


Figure 3.12 Volumetric water content of pipe-mole (○--○) and undrained (●—●) profile on two occasions in 1983. For depths where a (*) appears the difference between mean values for the drained and undrained plots was significant at $P \leq 0.05$.

iii) In a year of average rainfall, the water content of the surface soil is considerably lower in a drained soil than in an undrained soil for most of the winter-spring period.

iv) For most of the time, the rate at which the watertable declined was not determined by the carrying capacity of the moles or collecting pipes, but rather by the rate of water movement through the soil to the mole. The watertable was often about 200 mm shallower midway between moles than it was near the moles.

v) If, for most of the time, the greatest resistance to the movement of drainage water is water flow from the bulk of the soil to the mole, then the watertable could be lowered deeper in the profile more quickly by a closer mole spacing than the traditional 2 metres.

vi) For the two years immediately after their installation, there was no difference in watertable levels, discharge hydrographs or surface soil water content, between plots drained by pipe-mole or mole-mole drainage treatments. But further work is needed to assess the long term viability of mole-mole drainage systems.

CHAPTER 4

CHAPTER 4

THE EFFECTS OF DRAINAGE ON PASTURE UTILISATION, GROWTH RATES AND TREADING DAMAGE

4.1 Introduction

Two of the claimed benefits of drainage listed in Chapter 1 are increased pasture growth rates in spring and decreased treading damage to both soil and pasture. These benefits supposedly result from the lower watertable and surface soil water content induced by drainage. It was established in Chapter 3 that, in a year of average rainfall, mole drainage lowered the watertable level and consequently decreased the water content of the surface soil. In this chapter the effect of drainage on pasture utilisation during grazing and on subsequent regrowth rates will be discussed, as will the effect of drainage on treading damage.

Pastoral agriculture involves interaction between the animal, the soil and the plant. The grazing animal can rapidly and substantially alter both the productivity and botanical composition of a sward. Grazing over the winter-spring period is also often to the detriment of soil structure (Gradwell, 1968). These changes in pasture and soil properties are induced by defoliation, treading and excretion (Matthews, 1971; Curll and Wilkins, 1983).

Kellett (1978) found that pasture yield losses can be large if treading damage is not controlled. Estimates of losses under average grassland management range from 25-40%, with a 5-20% yield loss resulting from immediately damaged and buried herbage, and a further loss of 10-20% due to reduced production from the damaged sward.

Although the mechanisms by which treading damage affects the sward are understood, primarily due to the work of Edmond (1958, 1963, 1964, 1966), little actual field work has been carried out in New Zealand to determine the extent to which treading damage diminishes both utilization and regrowth. Many of the studies into the effect of treading have used large numbers of non-grazing animals, herded down a race, to tread pastures for brief periods of time (Edmond, 1966; Brown, 1968). This is quite different to normal pasture management and so the results are of limited applicability.

Also, although Edmond (1963) conducted experiments to investigate the effects of treading at different soil moisture levels, little work has been done to compare the extent of treading damage on drained and undrained soils. Only one research project on the effect of drainage on pasture production has been reported in New Zealand. In a field study conducted at Invermay Research Station, Scott (1963) concluded that where winter grazing is practised on wet soils, pasture production will suffer appreciably and that drainage will alleviate this damage. It is of interest to note that he also found drainage to be of doubtful value in increasing pasture production in the absence of winter grazing. This is in conflict with data presented by Hoogerkamp and Woldring (1967) which showed that lowering the watertable increased winter pasture production on an ungrazed heavy clay soil in the Netherlands. However, the findings of Gradwell (1967, 1969) tend to support the work of Scott. Gradwell found that perennial ryegrass and white clover are especially well adapted to growing in soil low in oxygen, so that draining a soil is unlikely to directly increase the growth rate of an ungrazed pasture sward. Overseas work has also suggested that the major benefits of drainage become apparent only when grazing occurs (Trafford, 1977).

Treading damage becomes most likely when the surface soil is near saturation, as soil aggregates are soft and unstable under very wet conditions (Edmond, 1966). This instability results in the soil becoming pugged when grazed. Important factors which determine the extent of treading damage of any given soil type are its water content, the quantity of ground cover and the type and number of grazing animals (Thomas and Evans, 1975). When the water content at the soil surface is high, the bearing strength of the surface soil is less than the hoof pressure and so treading damage results (Kellet, 1978).

If water in itself is not injurious to pasture growth, it remains to elucidate whether or not waterlogging has an adverse effect on pasture. In the next two chapters, studies of the effects of drainage on some plant and soil properties are described. In this chapter, analysis of pasture growth and utilisation data reveals some of the benefits of drainage and allows discussion of the mechanism that gives rise to these benefits.

4.2 Materials and Methods

4.2.1 Pasture production

Pasture production measurements were made by mowing a herbage sample (2.3 x 1.0 m) protected by a cage during grazing. This represented the herbage potentially available to stock, and by cutting an equal area of herbage from the grazed pasture the herbage not eaten by stock was measured simultaneously. The cage was then shifted to a new position. Pasture production over the regrowth period was obtained as the difference between the herbage dry matter inside the ungrazed cage and the herbage dry matter above mower height in the grazed area at the preceding harvest. Two large cages, each 3.3 m x 1.5 m, were used per plot. The cages were normally cut immediately after grazing. During set stocking the cages were cut before the pasture in the caged areas became so long that it could not be easily mown.

As an alternative technique, a capacitance pasture meter was also used to measure pasture production in the caged areas. The meter used was Model 8202, supplied by Design Electronics of Palmerston North. An advantage of the pasture meter was that measurements could be made more frequently than with the mowing technique.

4.2.2 Pasture utilisation

Pasture utilisation was calculated after residual dry matter had been measured using a small quadrat (0.4 m x 0.4 m) thrown randomly across the plots. The herbage it enclosed when it landed was cut at ground level with electric shears, bagged and oven-dried at 60°C to determine the mass of dry matter.

As an alternative technique, the capacitance pasture meter was also used to measure residual dry matter. The advantage of the meter is that it allows many readings to be taken on each plot. The meter was calibrated against known dry matter yields measured by the quadrat method described above. Time limitations over the spring months restricted the measurement of residual dry matter to drained Plots 4 and 8 and undrained Plots 5 and 7.

Standing herbage dry matter was also assessed visually.

The pasture meter underestimated the amount of herbage left on the undrained plot as it was unable to take into account the herbage that lay below the muddy surface. This resulted in the overestimation of utilisation on undrained plots. To avoid this problem when quadrats were cut, the areas of herbage inside the quadrat on the undrained plots were washed free from mud and stood upright before cutting. Because the herbage on the drained plots was so short, the electric shears tended to scatter the short lengths of pasture during cutting, making it difficult to collect all of the residual herbage and so underestimating the amount of residual dry matter. This resulted in a value for utilisation that was too high.

After grazing on certain areas of the undrained plots, pugging damage was less severe and the utilisation of pasture was greater than was the case for the rest of the plot. This variability in the amount of pugging damage and pasture utilisation within undrained plots can be explained by variability in watertable levels. As the watertable level has a direct bearing on pasture utilisation and on the extent of pugging damage, any variability in the level of the watertable is likely to be mirrored in both pasture utilisation and soil strength values. It was thought that by sub-dividing the undrained plots into wet and dry areas, as described in Section 3.3.1.2, the variability in such parameters as pasture utilisation could be understood better. Variability between plots due to location within the paddock can be taken into account by the experimental design used in this study.

Because of the range in watertable levels, and associated differences in the degree of utilisation and pugging damage, it was possible to correlate watertable levels with the degree of pugging damage and pasture utilisation. A ranking of 1 was given to areas where the herbage had been fully utilised, that is remaining grass was about 10 mm in length, while a ranking of 5 indicated that virtually none of the pasture had been eaten but had just been flattened into the mud. Details of the ranking scheme appear in Fig. 4.2.

4.2.3 Dung return to the plots

Dung return to the plots was measured using a quadrat (0.4 m x 0.4 m) which was thrown randomly thirty times within each plot, and the pieces of dung inside the quadrat counted. Sub-samples, consisting of thirty pieces of dung were placed in bags and returned to the laboratory. There they were oven-dried at 60^{o}C and weighed. Knowing the average weight of a piece of dung and the average number of pieces in the quadrat, it was possible to calculate the mass of dung returned per unit area on each plot.

4.2.4 Statistical analysis

Two statistical tests were used to establish the significance of differences between treatments. Where the data sets were large enough to warrant it, an analysis of variance was carried out according to the split-plot in time design (Little and Hills, 1972) and least significanct differences determined.

For smaller data sets, such as pasture utilisation during mob grazing or measurements of the quantity of dung returned to plots, a simple t-test was used.

4.3 Results

4.3.1 Effect of drainage on pasture utilisation in winter

4.3.1.1 1982 - a dry winter

During the winter of 1982 the research paddock was grazed by a mob of 2700 ewes on two occasions. The first grazing occurred in early June and the second in mid August. On both occasions utilisation was approximately 80% of the available pasture and grazing was even across the entire area on both drained and undrained plots. The watertable was about 450 mm from the surface in the drained and undrained plots during both grazings, and there was no heavy rainfall.

4.3.1.2 1983 - an average winter

In 1983, the research area which had a pasture cover of 2400 kg DM ha^{-1} was grazed by a mob of 2700 ewes, a stocking rate of 490 sheep ha^{-1}, for three days commencing on 21 July. The watertable was approximately 100 mm from the surface on the undrained plots as opposed to

400 mm on the drained plots. Treading damage to both the surface soil and the pasture sward on wet areas of the undrained plots was very severe as illustrated in Fig. 4.1. In contrast to the previous year, there were large differences in pasture utilisation between the drained and undrained plots as depicted in Fig. 4.2. Mean values for pasture utilisation on the drained plots (values for the pipe-mole and mole-mole plots have been combined) and the wet areas of the undrained plots are presented in Table 4.1. The visual assessment reported in Table 4.1 was done from photographs by a person experienced in visually estimating pasture cover. The pasture meter measured a utilisation increase of 19%, the quadrat cut method 34%, and the visual assessment an increase of 21%, due to drainage. As discussed above, the poor agreement between the absolute values obtained using the different techniques is expected considering the muddy state of the soil and pasture at the time of measurement. However, all measurement techniques gave highly significant differences ($P \leq 0.01$) in utilisation between wet areas of the undrained plots and the drained plots.

It must be stressed that the utilisation values reported here are for the wetter areas of the undrained plots. For the small drier areas on these plots, utilisation was somewhere between the extremes observed on the drained plots and the wet areas of the undrained plots, and was dependent on watertable depth.

Results of the visual ranking of pasture utilisation around each of the watertable observation wells appear in Table 4.2. When the watertable was about 50 mm from the surface, severe pugging damage and poor pasture utilisation were observed. Even when the watertable level was 110 mm below the surface, the soil sustained an unacceptable amount of damage and pasture was under-utilised. It was concluded that a watertable depth shallower than 200 mm was likely to cause severe pugging damage and

Figure 4.1 Plate illustrating the severity of treading damage on undrained plots (Plot 7) after the July, 1983 grazing. Note how the surface soil was smeared so that it buried pasture.

Plot 8

Plot 5

Figure 4.2 Plates illustrating difference in pasture utilisation between drained (Plot 8) and undrained (Plot 5) plots after the July, 1983 grazing.

Table 4.1 Pasture utilised during mob grazing in July, 1983.

Mean values for a particular measurement technique followed by a different letter are significantly different at $P \leqslant 0.01$.

	Utilisation (%)		
Technique Plots	Quadrat	Meter	Visual
Undrained	65 a	58 a	45
Drained	99 b	77 b	66

Table 4.2 Relationship between pasture utilisation, pugging and depth to the watertable observed in July, 1983.

Mean values of a parameter followed by a different letter are significantly different at $P \leqslant 0.01$.

	Site conditions		
Parameters measured	Severe pugging	Slight pugging	Unpugged
Visual assessment of pasture utilisation	5 (Poor)	3	1 (Good)
Pasture utilisation measured using quadrat method (%)	65a	*	99b
Mean depth to Watertable (mm)	50a	110a	275b

*No measurement made.

poor pasture utilisation.

4.3.1.3 1984 - an average winter

Though very large and important differences were found in the amounts of herbage utilised by the animal on the drained plots compared with the undrained plots in 1983, the interesting question remains as to whether or not utilisation would have been as poor on the wet areas of the undrained plots if the sheep had not had the option of grazing and camping on drained plots. That is, could they have been forced to utilise more pasture on the undrained plots? To go some way towards answering this question it was decided that the mob grazing in 1984 would be carried out in a slightly different manner. Instead of grazing the entire paddock for three days, the paddock was divided into three strips, each strip containing one replicate of the three drainage treatments. The entire mob of 2700 sheep was placed on each strip for a period of one day, giving a stocking rate of 1470 ewes ha^{-1}, three times the stocking intensity of 1983. The aim in using such a high stocking rate was to force the sheep both to utilise the herbage on the wet areas of the undrained plot, and to spend some time camped there.

During each of the three days the sheep spent on the research area (20 - 22 July), it was observed that they still avoided the undrained plot where the watertable level was approximately 30 mm below the surface and preferred to congregate on the two drier drained plots where the watertable was approximately 420 mm below the surface. This was borne out in the utilisation data obtained and presented in Table 4.3. These data were obtained using the pasture meter, and it is noted that variability between plots is small. The mean utilisation for the drained plots was 83% whilst that for the wet areas of the undrained soils was 48%, a highly significant ($P \leqslant 0.01$) difference of 35%. Despite the fact that in

Table 4.3 Pasture utilised during mob grazing in July, 1984, measured using the pasture meter.

Pasture Utilisation			
Drained plots			
Plot	Pre-grazing (kg ha^{-1})	Post-grazing (kg ha^{-1})	Utilisation (%)
1	1940	370	81
2	1930	320	83
4	1990	290	85
6	1680	280	83
8	1740	320	82
9	1820	320	82
Undrained plots			
3	1820	950	48
5	2010	860	57
7	1660	1000	40

1984 the stocking rate was three times what it had been in 1983, utilisation was even poorer than that measured in 1983 on the wet areas of the undrained plots.

Fig. 4.3 shows the effect that watertable height has on pasture utilisation, along with the 1 to 5 scale detailing the ranking scheme. A watertable level closer to the soil surface than 100 mm is associated with severe pugging damage and very poor utilisation. A watertable level below 300 mm will ensure little pugging damage and good utilisation. When the watertable level was between 150 and 250 mm, the pugging damage sustained by the soil, and the quantity of herbage utilised, ranged between values that are poor (ranking 3 and 4) to moderate (ranking of 2). These results confirmed the watertable level of 200 mm proposed in 1983 as being the minimum depth needed on the Tokomaru silt loam for good pasture utilisation by sheep and minimal pugging damage.

4.3.2 Effect of drainage on pasture utilisation in spring

4.3.2.1 1983 - an average spring

As already described in Chapter 2, the research paddock was set stocked with 17 ewes ha^{-1} in August 1983 and this grazing pressure was maintained throughout lambing and until the end of the year. Rainfall for the spring of 1983 was about average so that on many days the watertable was less than 200 mm from the soil surface on the undrained plots, as shown in Fig. 3.4. A consequence of shallow watertables was that the poor utilisation observed for the winter mob grazing on the undrained plots continued on into spring.

The differences in the amount of pasture remaining on the wet areas of undrained Plots 7 and 5 and the drained Plots 8 and 4, as measured in the spring of 1983 by the quadrat cutting technique, are shown in Fig. 4.4. Between 300 and 450 kg ha^{-1} more pasture was left standing on the wet areas

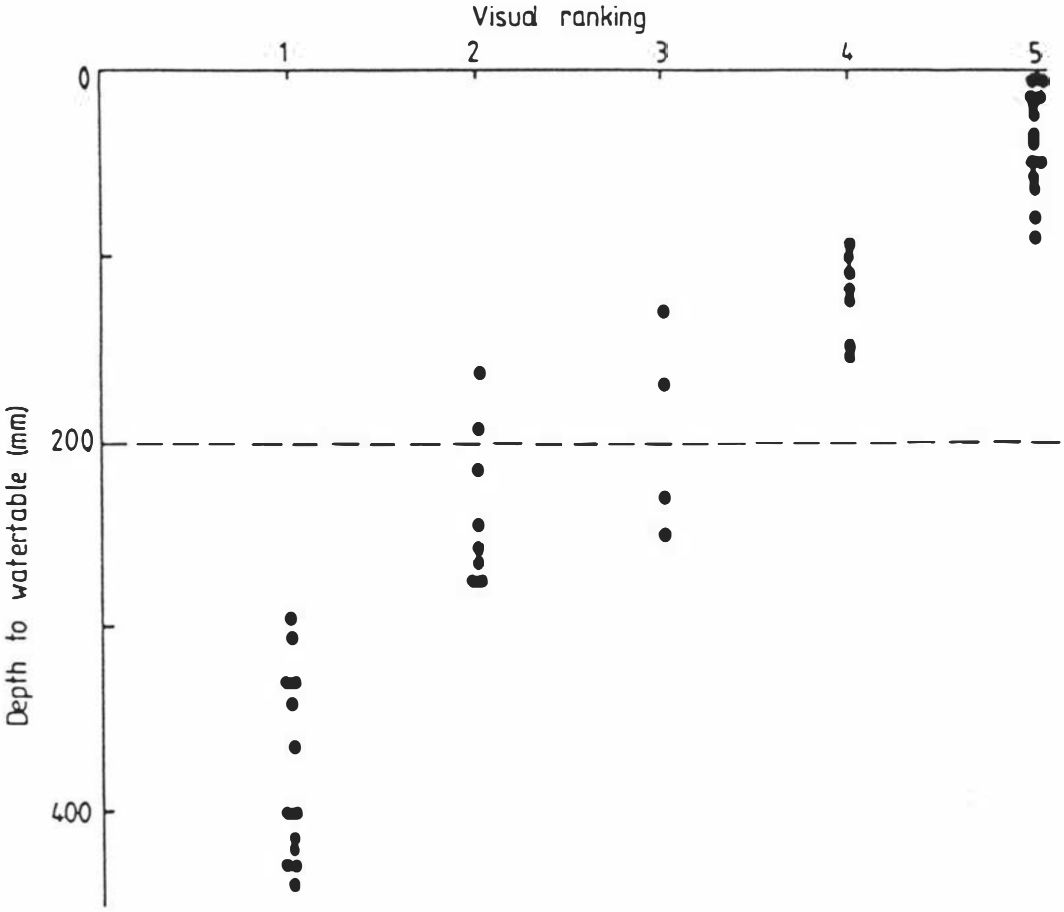


Figure 4.3 Effect of watertable level on pasture utilisation. The rankings used were:-

1. Fully utilised - remaining herbage approximately 10 mm in length.
2. Moderate utilisation - remaining herbage 20 to 30 mm in length.
3. Approximately one half of the pasture utilised - remaining herbage about 50 mm or greater in length.
4. Top of pasture utilised - most of the herbage was flattened and uneaten.
5. No herbage eaten - herbage just flattened into the mud .

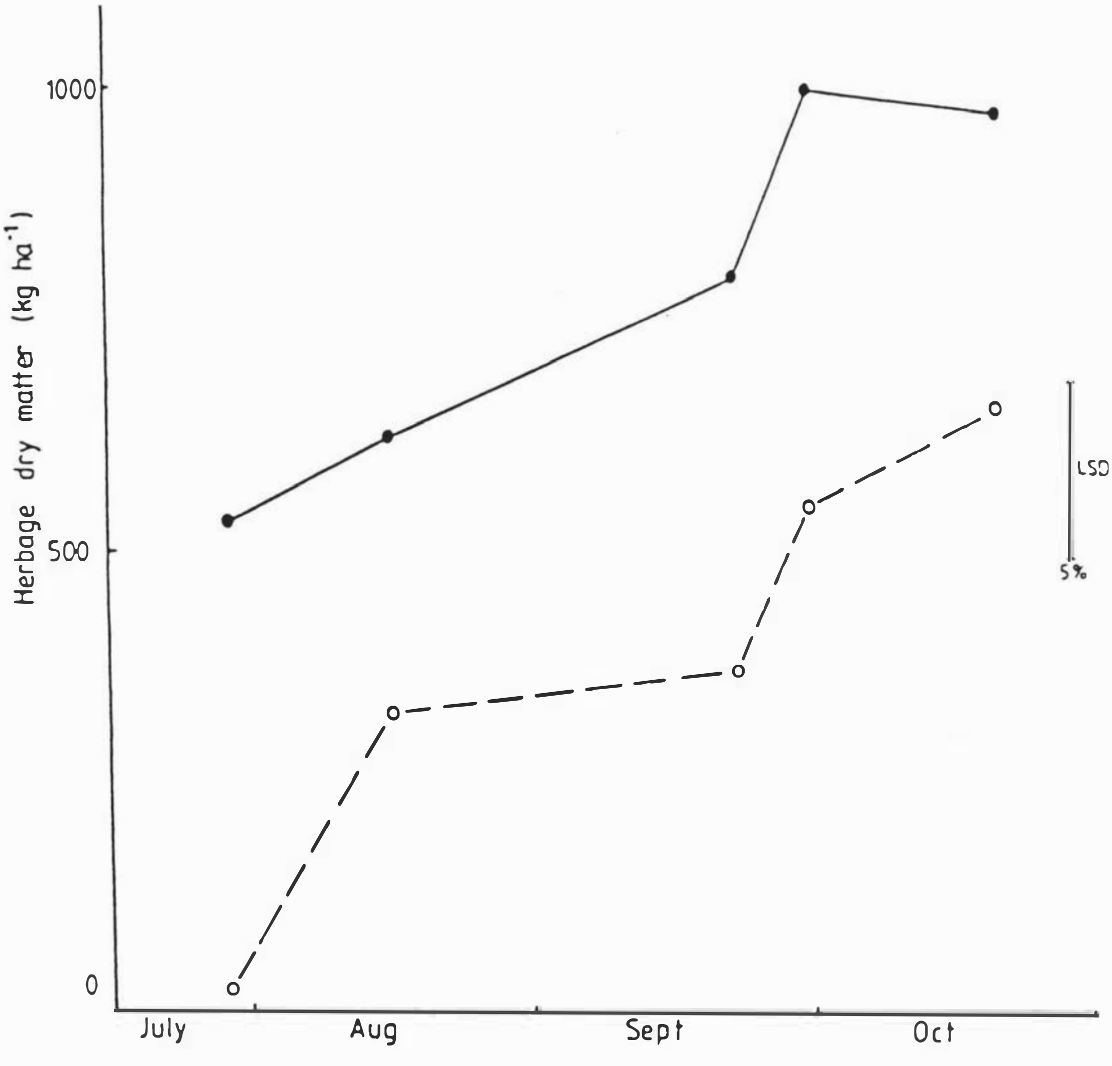


Figure 4.4 Mean values of pasture cover on the pipe-mole (○- -○) Plots 4 and 8 and undrained (●—●) Plots 7 and 5 measured using the quadrat technique. Least significant difference (LSD) at the 5% level .

at the time of measurement than on the drained areas. These differences between drained and undrained plots were significant at $P \leqslant 0.05$.

Data for standing dry matter on Plots 4, 8, 5 and 7, measured using the pasture meter, are shown in Fig. 4.5 and confirm the results presented in Fig. 4.4. Between August and late October there was on average 35% more dry matter on the undrained plots than on the drained plots, but by the end of spring, the quantity of pasture present on the drained plots and wet areas of the undrained plots was similar.

The greater quantity of pasture measured on the wet areas in the spring period was not due to higher growth rates on these plots (Section 4.3.3.3) but rather because the sheep were not utilising the pasture present. Although the severe treading damage observed during mob grazing in winter was no longer occurring, the sheep were still finding much of the pasture on the undrained plots too soiled or old and unpalatable to eat.

4.3.2.2 Differences in Camping Behaviour

Differences in dung return to the plots showed that the sheep preferred to camp on the drained plots. Measurements of the amount of dung present on drained and undrained plots on two spring days in 1983 appear in Table 4.4. In both October and November the differences in dung return to drained and undrained plots were highly significant ($P \leqslant 0.01$). In October, on average, there was approximately five times as much dung on the drained plots, while in November there was approximately a threefold difference. This diminishing difference between drained and undrained plots is in keeping with the smaller differences in watertable levels and pasture utilisation observed towards the end of spring.

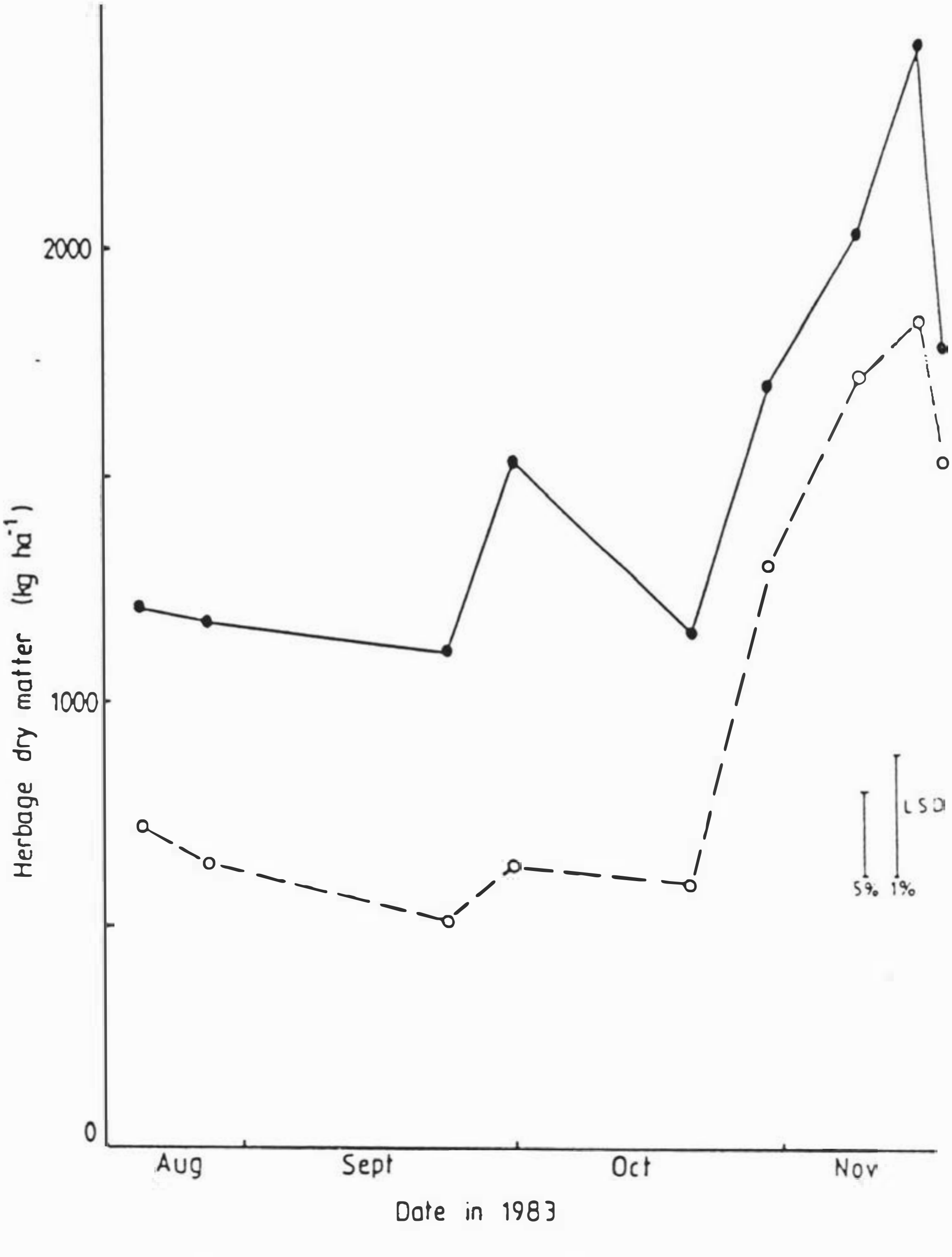


Figure 4.5 Mean values of pasture cover on the pipe-mole (O--O) Plots 8 and 4 and on the undrained (●—●) Plots 7 and 5 measured using the pasture meter. Least significant difference (LSD) at the 1% and 5% level .

Table 4.4 Mean values for the density of dung on drained and undrained plots.

Mean values for a particular date followed by a different letter are significantly different at $P \leqslant 0.01$.

	Density of dung on plots ($g\ m^{-2}$)	
Date in 1983	Drained	Undrained
3/10/83	72 a	13 b
15/11/83	82 a	28 b

4.3.3 Effect of drainage on pasture production

4.3.3.1 1981 - background year

The uniformity of the plots was established in the first year of the study prior to installation of drainage. Fig. 4.6 depicts pasture production during the year 1981, measured using the mowing technique described in Section 4.2.1. There were no significant differences in pasture production between the plots at any harvest.

4.3.3.2 1982 - a dry year

In the dry year, mole drainage did not significantly affect pasture production. Pasture production as measured by the mowing technique in the relatively dry year 1982 is shown in Fig. 4.7. Because pasture production on the pipe-mole and mole-mole plots was almost identical the values for the 6 plots were averaged and termed 'drained'.

4.3.3.3 1983 - an average year

In a year of average rainfall, mole drainage had a significant effect on pasture production. Pasture growth rates for 1983, as measured by the mowing technique, are shown in Fig. 4.8. The values for the least significant difference (LSD) at the 1% and 5% level can only be used to test the significance of differences in Fig. 4.8 after July, the time of mob grazing. There was no significant difference in growth rates between drained and undrained plots for the first half of the year, that is up until the end of July, when the mob grazing occurred. After the winter grazing, during the months of August, September and October and to a lesser extent November, pasture production was significantly ($P \leq 0.05$) higher on the drained plots than it was for the wet areas of the undrained plots. Regrowth was 74% higher on the drained area than on the wet areas for the August - September

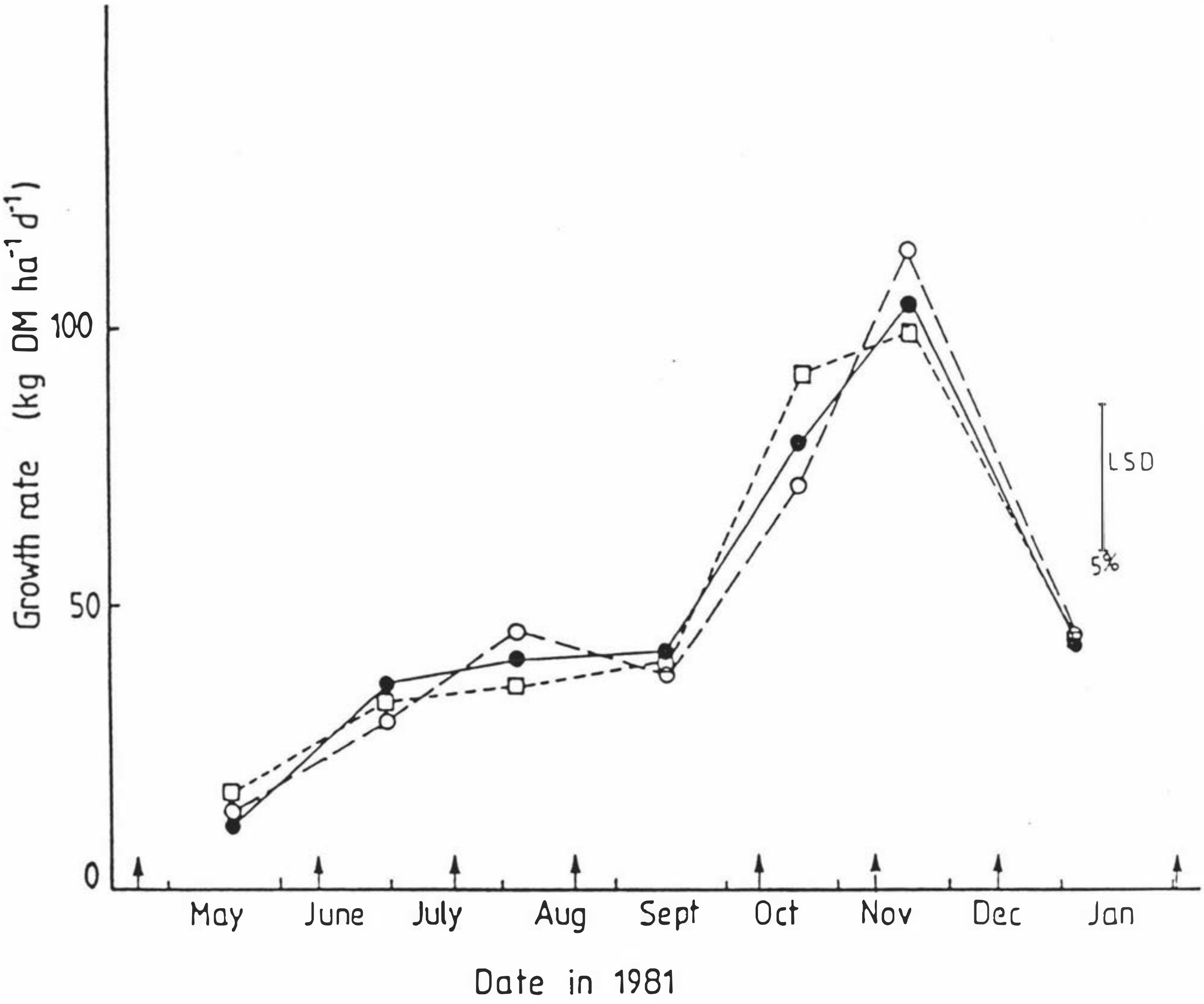


Figure 4.6 Pasture growth rates in 1981 for pipe-mole (○--○), mole-mole (□··□) and undrained (●—●) plots measured using the mowing technique. Mean values are drawn at the mid-point between harvest dates (↑). Least significant difference (LSD) at the 5% level .

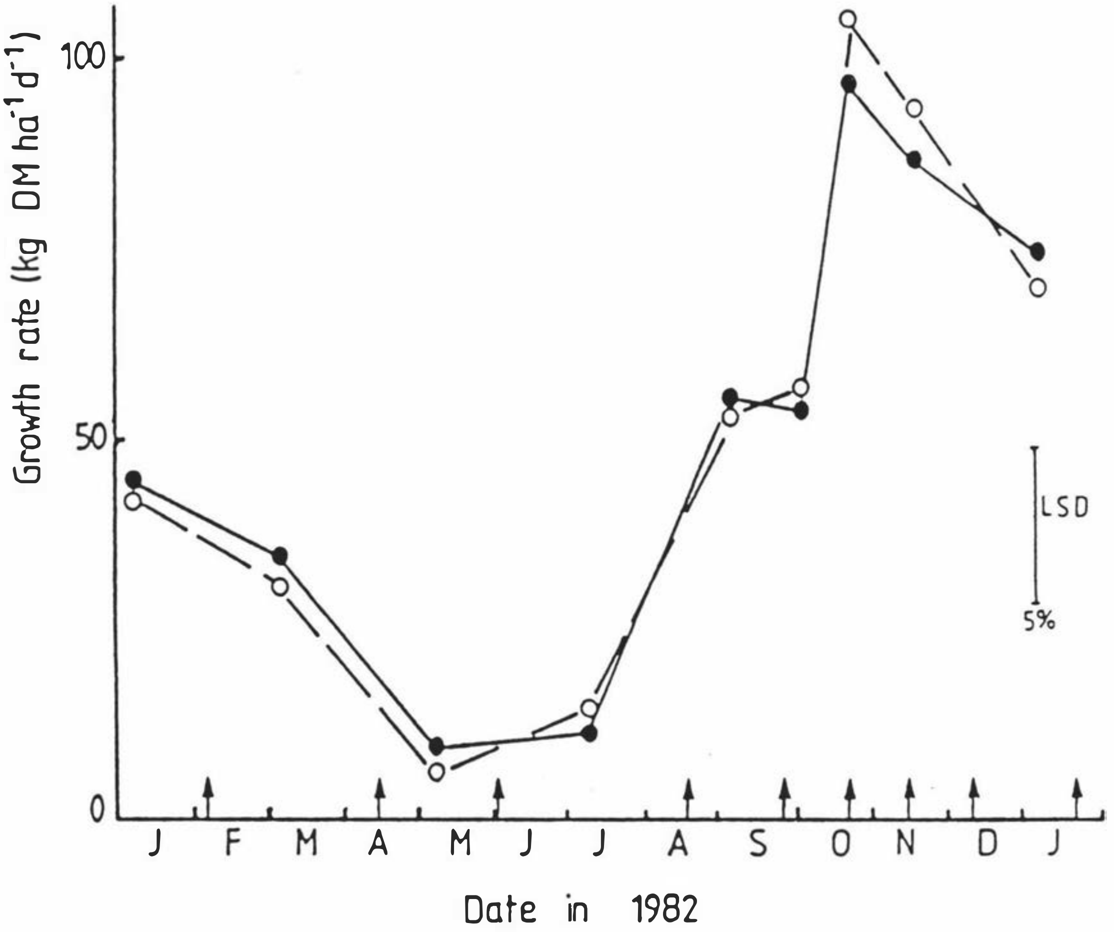


Figure 4.7 Pasture growth rates in 1982 for drained (O--O) and undrained (●—●) plots measured using the mowing technique. Mean values are drawn at the mid-point between harvest dates (↑). Least significant difference (LSD) at the 5% level .

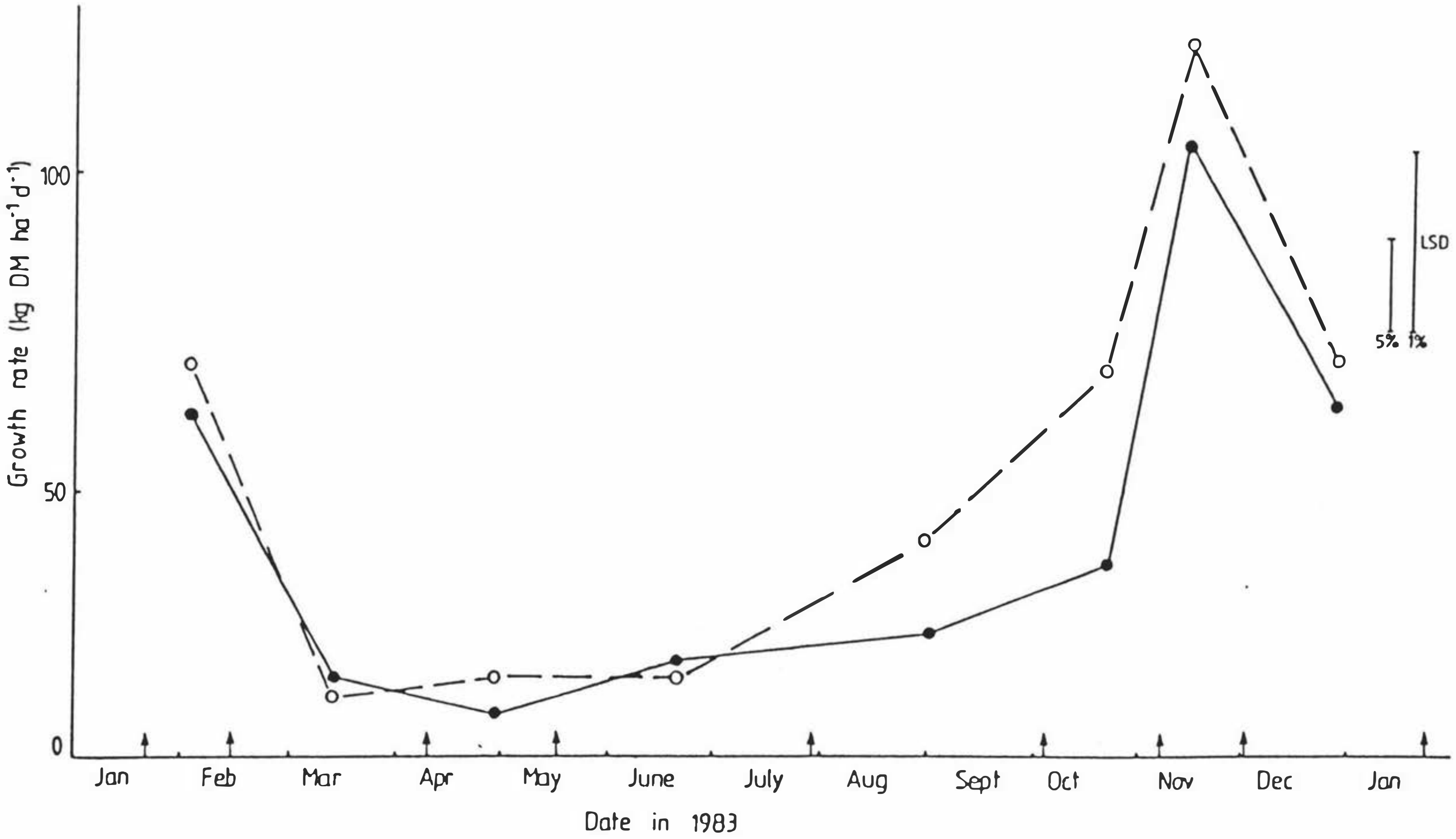


Figure 4.8 Pasture growth rates in 1983 for drained (O--O) and undrained (●—●) plots measured using the mowing technique. Mean values are drawn at the mid-point between harvest dates (↑). Least significant difference (LSD) at the 1% and 5% level for harvests after July .

period and 49% higher for the October - November period. Between July and January a total of 2500 kg ha^{-1} more dry matter grew on the drained soil than on the wet areas. This is equivalent to a 30% increase in the amount of pasture produced on the drained plots over the wet areas of the undrained plots for the period July to January.

Similar results for growth rates in the caged areas were obtained using the pasture meter, as illustrated in Fig. 4.9. Significant (often at $P \leq 0.01$) differences in regrowth rates extend from the time of mob stocking in July through to November. The extra herbage produced on the drained soil compared to the wet areas was 1550 kg ha^{-1}, a 30% increase. The pasture meter data concur with the results obtained by cutting the area within the cages, in that both show that, following grazing, production was 30% higher on drained plots than on undrained plots.

It should be mentioned again, that the data quoted for growth on the undrained plots are for the wet areas of the plots as defined in Section 3.3.1.2. Though these wet areas made up 80% of the undrained plots, if the remaining 20% of the plots had been included then average growth rates for the undrained plots would have been somewhat higher. The undrained plot which would have been most affected was Plot 3, as one third of its area was drier than the rest of the undrained plots. For this drier portion of Plot 3, pasture growth was almost the same as that measured on the drained plots.

4.4 Discussion

A separate study undertaken at the research site (Climo and Richardson, 1984) has shown that a relationship exists between the matric potential at the top of the soil profile and resistance to penetration. Resistance to penetration changes dramatically over a comparatively narrow range of matric potentials and corresponding gravimetric water

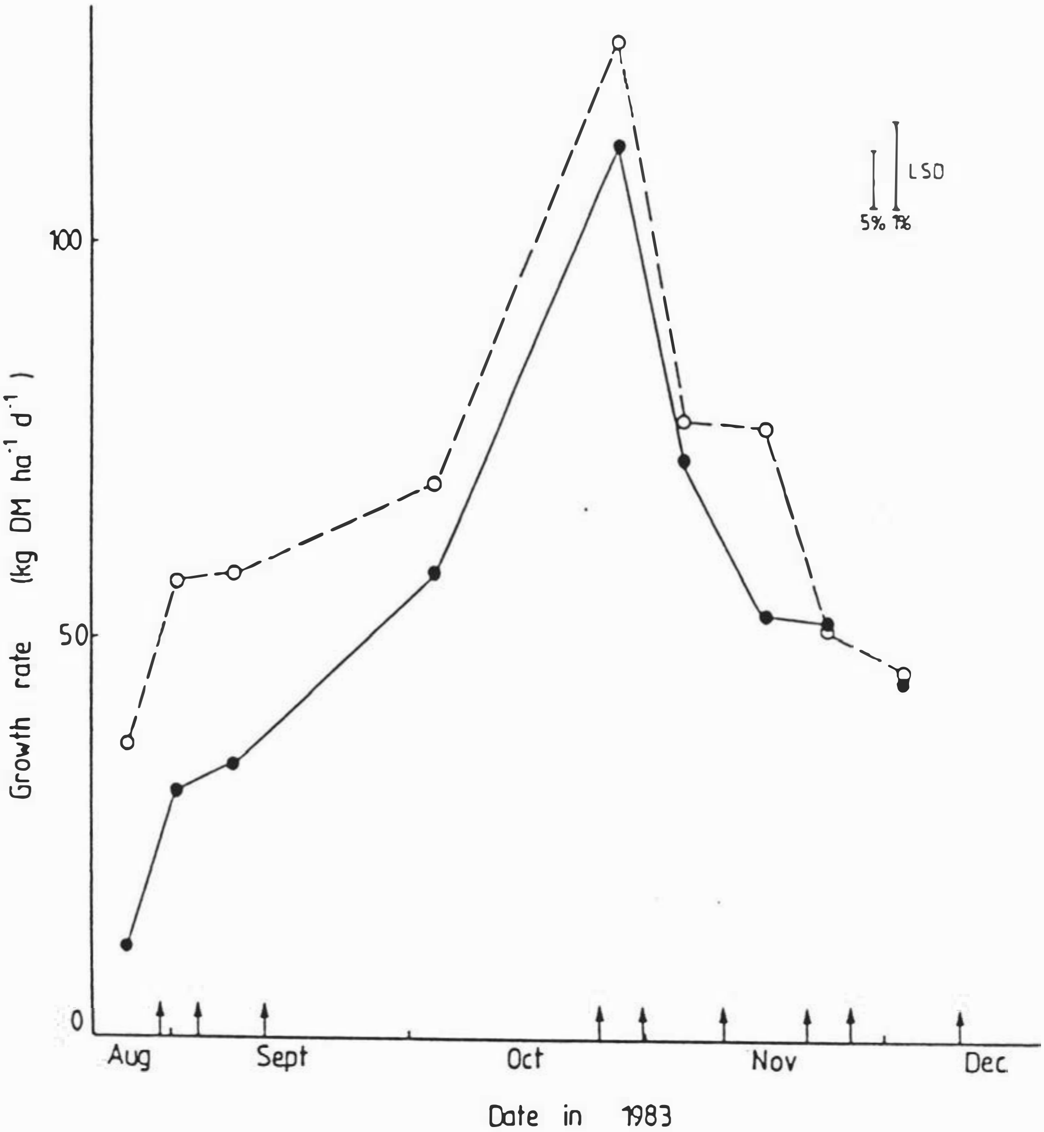


Figure 4.9 Pasture growth rates in 1983 for drained (O--O) and undrained plots (●—●) measured using the pasture meter. Mean values are drawn at the mid-point between harvest dates (↑). Least significant difference (LSD) at the 1% and 5% level .

contents. A decrease in soil strength and bearing capacity, along with the related increase in susceptibility to damage at high water contents has also been reported by other workers (Gradwell, 1965; Edmond, 1966; Massey et al., 1974).

Static loads for sheep and cattle have been estimated to be between 80 to 400 kPa (Kellett, 1978). Climo (pers. comm.) found that serious treading damage was likely when the resistance to penetration of Tokomaru silt loam was less than values 0.2 to 2 times the static load for sheep (200 kPa) which corresponded to a water content in the top 30 mm of the soil profile of approximately 0.6. There were many days in the winter-spring period of 1983 during which the water content of the soil at the surface of undrained plots was much greater than 0.6 (Fig. 3.11). On these days, soil strength would have been low and therefore damage to both soil and pasture would be likely to result from grazing. The drained soil on the other hand was usually drier than the undrained soil, so that it would have a higher bearing capacity and could support the grazing animal, thus incurring less damage.

The difference in the extent of treading damage between the drained and undrained plots was most evident following mob stocking for three day periods in July of 1983 and 1984. On the undrained plots, treading damage was severe with pugging of the soil surface and the burial of pasture in the mud. In contrast, soil structure on the drained plots was observed to be relatively unaltered by the hoof of the sheep and damage to pasture was kept to a minimum.

Treading damage and soiling of pasture was the likely cause of the poor utilisation by grazing sheep under both mob and set stocking. Smearing and severe pugging of the soil surface, and trampling of the herbage into the mud occurred during grazing of the undrained plots in wet conditions. Because the soil surface on the undrained plots was wet the sheep grazed preferentially the drained plots, and even when these plots had been stripped of available pasture, the buried and soiled herbage on the undrained plot was unpalatable and was not grazed.

The difference in utilisation measured after mob grazing in 1983, of approximately 25% for pasture on a wet and dry soil equates to a difference in animal intake of approximately 400 - 500 kg DM ha^{-1}; a large quantity of pasture, particularly in winter or early spring. An increase in the quantity of pasture the animal is able to utilise if grazing occurs during a wet period in winter or spring is an important benefit of drainage. Similar results are presented by Scott (1963) and Kellett (1978).

The results obtained from the mob grazing in 1984 show that, even under pressure, the grazing animal is unable or unwilling to utilise pasture grown in wet areas. When the stocking rate was increased, instead of pressure of numbers forcing the grazing of wet areas, the greater number of hoofs only increased the amount of damage done to the pasture and soil on the wet areas. Though the validity of any conclusions drawn concerning a decrease in utilisation with increasing stocking rates on undrained soils may be questionable, the 1984 results do clarify the mechanism by which the availability of herbage to the animal is reduced.

The pattern of dung return shows that animals avoid camping on areas where it is wet underfoot. Few general conclusions can be drawn concerning the effects of dung distribution on soil fertility because in this experiment the animals had the option of camping on either drained or undrained plots. Normally, an entire paddock would be either drained or undrained and the distribution of dung would be more uniform. One reason for draining wet areas of a particular paddock would be to minimise non-uniform nutrient return due to stock avoiding wet areas.

The marked difference in pasture recovery or regrowth rates between drained and undrained plots in 1983 is also most likely attributable to the severe damage done to the pasture on the undrained plots by the hoof of the animal during the mob grazing, and subsequently during set stocking. As mentioned previously, at the time of mob grazing the surface soil quickly became muddy so that much of the pasture was trodden into these large areas of puddled soil by the sheep, and was buried. As a consequence of this damage,regrowth rates were low. The 30% increase in the amount of pasture produced on the drained plots over the wet areas is comparable to the 20% increase in production that Kellet (1978) found from an undamaged sward compared to a sward damaged during grazing. Likewise Curll and Wilkins (1983) found treading under set stocking induced a 25% reduction in herbage growth rates.

Other workers have also shown that treading damage can significantly reduce subsequent herbage yields (Edmond, 1958, 1964, 1970; Scott, 1963; Brown, 1968). This reduction has been attributed to a decline in plant numbers after grazing, due to leaf crushing and bruising (Edmond, 1958, 1963; Hudson et al., 1962), and a reduction in tiller density (Edmond, 1958; Campbell, 1966; Matthews, 1971). Kellett (1978) states that animals grazing on firm ground do relatively little damage to growing points. But on soft soil treading damage occurs and many growing points are broken and buried. Treading also induces indirect effects on pasture growth through soil compaction and puddling (Gradwell, 1960, 1965).

It is unlikely that the greater dung return to the drained plots enhanced growth rates. Soil test values (Section 5.3.3.2) showed that the soil at the research site was not deficient in the major nutrients so that a large response in growth rates would not be expected if nutrients were added to the soil.

The data obtained in 1983 and 1984 relating watertable depth to pasture utilisation and pugging damage indicated that a watertable level of 200 mm was the minimum depth needed in the Tokomaru silt loam to avoid treading damage by sheep. To this depth was attached the arbitrary but useful notation of safe/unsafe grazing. If the watertable was shallower than a level of 200 mm from the soil surface then grazing would most likely cause severe damage to the soil structure, poor pasture utilisation and impaired regrowth rates; such a day was termed unsafe for grazing. If the watertable was deeper than a level of 200 mm from the surface, it was most likely that grazing would be safe, in that pugging damage, pasture utilisation and regrowth rates would be at levels which were acceptable. On a similar soil type, Lagocki (1978) also found for sheep grazing, that the bearing strength of the trampled soil was low when watertables were less than 200 mm from the surface.

4.5 Conclusions

The following conclusions may be drawn:

i) The benefits of drainage under pasture only become apparent once grazing commences on wet soil. The benefits are improved pasture utilisation during grazing and greater subsequent regrowth rates.

ii) Drainage increased pasture utilisation by approximately 25% during mob grazing on a winter day when the surface soil was wet. Drainage also increased pasture utilisation under set stocking in spring.

iii) Drainage increased pasture production by 30%, from the time of mob grazing in winter to mid summer, in a year with average rainfall.

iv) Treading damage to the plant was apparently the major cause of poor pasture utilisation and impaired growth rates on the undrained plots.

v) The extent of treading damage to both plant and soil was related to the watertable depth. The benefits of drainage arise primarily because mole drainage lowers the water content of the surface soil, which increases the bearing strength and therefore lessens the extent of treading damage.

vi) For the Tokomaru silt loam, the minimum watertable depth needed to avoid pugging damage from sheep and for good pasture utilisation and regrowth, was approximately 200 mm. If the watertable is deeper than 200 mm then sheep grazing is usually safe.

vii) In a dry year (such as 1982), the benefits of drainage are minimal because there are very few days when the watertable is shallower than 200 mm on either drained or undrained soil. However, because of the important benefits afforded by drainage in average or wetter years there can be little doubt that drainage is worthwhile.

CHAPTER 5

CHAPTER 5

THE EFFECTS OF DRAINAGE ON THE BOTANICAL AND CHEMICAL COMPOSITION OF PASTURE AND ON THE PLANT ROOT SYSTEM

5.1 Introduction

In Chapter 4 the effect of drainage on pasture utilisation during grazing in both winter and spring was described. The effect of drainage on pasture growth rates was also discussed. Quantity is only one property of the pasture sward; also of considerable importance is the quality of the pasture. Pasture quality has two aspects, firstly there is the botanical composition of the sward, and secondly the chemical composition of the plant tissue. The effect of drainage on the below-ground parts of the sward, namely the root system, should also be considered.

The work of Edmond (1962, 1963, 1964, 1966) has shown that treading damage can cause a substantial alteration to the botanical composition of a pasture sward. He found that the sward changed in that species more tolerant of treading damage, such as perennial ryegrass, tended to dominate at the expense of those that were more sensitive to treading, such as white clover. However, Scott (1963) found that white clover and ryegrass were relatively insensitive to treading during winter grazing of undrained soil and only the cocksfoot (Dactylis glomerata) and Yorkshire fog (Holcus lanatus) components of the sward were appreciably reduced.

The botanical composition of a sward can be an indicator of the moisture conditions in the soil. However, there have been few studies of the relationship between drainage and botanical composition. Minderhound et al. (1960) found that with less effective drainage, more water tolerant species were found in the sward. However, in contrast Hoogerkamp and Woldring (1967) reported that for well-fertilized and intensively stocked grassland the changes in the botanical composition related to the groundwater level were small.

Good aeration and moisture conditions throughout the greater part of the soil profile stimulate the growth and development of roots in all directions (Rowe and Beardsell, 1973). Ideally an extensive deep root system explores a larger soil volume for water and nutrients by the intensive contact of root hairs which are formed more profusely when the external supply of oxygen is adequate (Russell, 1977). If during their development, roots meet a waterlogged zone with reduced aeration, their growth will be suppressed. Daubenmire (1959) describes the effects of reduced aeration conditions on root development as follows:

i) Roots are shorter and root systems occupy less space and become shallow;

ii) Roots may be less numerous, root branching less complex, and root hair formation is usually suppressed;

iii) Development of adventitious roots from the base of the stem is often stimulated; these roots are better adapted to conditions of poor aeration than are the original roots;

iv) The respiration of the roots changes from ærobic to anaerobic with a consequent accumulation of toxic by-products and a reduced release of energy from the same amount of carbohydrate;

v) The rate of absorption of water and nutrients, and the rate of transpiration are reduced.

Although the effects of waterlogging on the root network of crops and fruit trees have been studied in detail, little attention has been given to the performance of the root system of pasture when it is subjected to excessive soil moisture. Gradwell (1967, 1969) found that grass and clover roots are relatively tolerant of anaerobic conditions and shoot growth was not adversly affected when the oxygen diffusion flux (measured with a bare platinum electrode) dropped to 1 x 10^{-7} g $cm^{-2}min^{-1}$, a value prohibitive to the root growth of most other species.

One of the claimed benefits of drainage mentioned in Chapter 1 is that it encourages a more extensive and deeper rooting system which can extract nutrients from a greater volume of soil and reduce the adverse effects of drought. To determine whether or not there was any substance to this claim, use was made of two radioactive tracers to compare the pattern of nutrient uptake on undrained plots with that on drained plots. Isotope data were analysed using the concept of root activity which has been used by several workers (Jackman and Mouat, 1972; Brash, 1973; Gregg, 1976; Gillingham, 1978; Syers et al., 1984).

An important assumption in all tracer studies is that when the tracer is introduced into the system, it forms an equilibrium between the different phases, which are in constant exchange (Newbould, 1969). If this assumption is satisfied then plants will absorb the tracer and nutrient in direct proportion to their occurrence in solution. The quantities of the available nutrient (for example ^{32}S) and tracer (^{35}S) adsorbed from a soil compartment can then be related as follows:

$$^{32}S_p/^{35}S_p = k_f \; ^{32}S_s/^{35}S_s \qquad (5.1)$$

where the subscripts p and s denote the amount of isotope present in the plant and soil respectively, and k_f is a constant reflecting the proportion of the pool of labile nutrient sampled by the plant. The value of k_f at different depths is usually assumed to be very similar and this was found to be the case by Nye and Foster (1960). Assuming k_f is constant at all depths, relative root activity in compartment i (RRA_i) may be defined as follows:

$$\mathrm{RRA}_i = 100\ {}^{32}S_{s,i}\ {}^{35}S_{p,i} / \sum_{i=1}^{n} {}^{32}S_{s,i}\ {}^{35}S_{p,i} \qquad (5.2)$$

where n is the number of compartments. Reviews of the conditions that need to be satisfied for this equation to be valid are presented by Fried and Broeshart (1967), Newbould (1969) and Brash (1973).

No research appears to have been carried out in New Zealand or overseas to determine the effect of drainage on the concentration of nutrients in pasture herbage. Neither has there been any comprehensive investigation into the effect of drainage on the plant root network of pasture. The changes in these important characteristics of the sward induced by drainage, along with alterations in botanical composition are discussed in this chapter.

5.2 Materials and Methods

5.2.1 Botanical composition

Botanical composition was determined using two different techniques. The first involved dissection of samples taken when the caged areas were harvested in 1982, 1983, and part of 1984. A sample of approximately 100 g of pasture was removed by clipping from the caged area (before the two strips were mown). After thoroughly mixing the pasture sample, the botanical composition of approximately half the sample was determined. The sub-sample was dissected into three categories; (i) grasses (mainly perennial ryegrass (*Lolium perenne*) and browntop (*Agrostis tenuis*), with some annual poa (*Poa annua*) sweet vernal grass (*Anthoxathum odoratum*), danthonia (*Notodanthonia clavata*) Yorkshire fog (*Holcus lanatus*), and timothy (*Phleum pratense*)); (ii) clovers (mainly white clover (*Trifolium repens*) and subterranean clover (*Trifolium subterraneum*). with some red clover (*Trifolium pratense*) and lotus major (*Lotus pedunculatus*)); and (iii) weeds (buttercup (*Ranunculus repens*), pennyroyal (Mentha pulegium), hawkbit (Leontodon taraxacoides), hawksbeard (Crepis capillaris) and daisy (Bellis perennis)). After dissection, composition was determined gravimetrically on a dry matter basis.

The second method, point analysis, was carried out on the research area in December, 1983, and April, 1984. A grid with three prongs 100 mm apart was placed every three metres along the diagonals of each plot and the species directly below each needle indentified. The species were divided into the following categories; perennial ryegrass, other grasses, clovers, buttercup, weeds, bare ground and dead material.

5.2.2 Chemical composition of pasture

Total phosphorus (P), nitrogen (N), and sulphur (S) levels in grass and clover were determined for selected samples collected when the caged areas were harvested in 1983 and part of 1984. Levels of P and N were measured following Kjeldahl digestion, by the autoanalysis method of Twine and Williams (1971). The concentration of S in herbage samples was determined using an induction furnace (leco model 632-300) in conjunction with an automatic titrator (Leco model 632-000). The method is detailed in Laboratory Procedures for the Soil and Plant Analysis Laboratory (Anon, 1977) and by Tabatabai and Bremner (1970). Because of time constraints and the observation that differences in levels of S for herbage grown on the drained and undrained plots were neither large or long lasting, fewer samples were analysed for S than for P and N.

5.2.3 Soil nutrient status

Twenty soil cores, 20 mm in diameter and 75 mm in depth, were removed from each plot using a soil corer. The cores were bulked, air dried and passed through a 2 mm sieve before analysis. In the dry year, 1982, cores were taken bi-monthly whereas in the winter-spring of 1983 and summer of 1984 sampling was carried out monthly. Soil pH was measured with a combination electrode after stirring 10 g of soil in 25 ml of distilled water and leaving to stand overnight.

Available phosphorus (H_2PO_4-P) was estimated using the bicarbonate method of Olsen et al. (1954). This involved shaking 1 g of soil mixed with 20 ml of 0.5M $NaHCO_3$ for 30 min in 50 ml polycarbonate centrifuge tubes on an end-over-end shaker at 0.3 Hz at 20°C. On completion of shaking the samples were centrifuged at 167 Hz for 5 min in a Sorvall RC2-B centrifuge (at 5°C) and the extracts passed through a membrane filter (< 0.45 μm). Inorganic P in aliquots of the extracts was determined by the Watanabe and Olsen (1965) modification of the Murphy and Riley (1962) method, except that the bicarbonate extracts were not neutralized prior to colour development. Absorbance was measured at 712 nm using a Pye Unicam SP 1800B spectrophotometer.

Available sulphur (SO_4-S) was determined as follows: 5 g of soil were shaken with 25 ml of 0.04M $Ca(H_2PO_4)_2$ (Searle, 1979) for 16 h on an end-over-end shaker at 20°C, centrifuged (5 min at 167 Hz) then membran filtered (< 0.45 μm) and an aliquot of solution retained. The aliquots were dried down over-night, analysed by the method of Johnson and Nishita (1952) and compared to standards in the range 0-80 μg S using a Pye Unicam SP 1800B spectrophotometer at 670 nm.

Ammonium (NH_4-N) and nitrate (NO_3-N) were determined as follows; 4 g of soil were shaken with 40 ml of 2M KCl for 20 min on an end-over-e shaker at 20°C; centrifuged at 167 Hz for 5 min, then filtered (< 0.45 μ NH_4-N was determined seperately from NO_3-N according to the procedure outlined by Bremner and Keeney (1966).

5.2.4 Relative root activity

Either radioactive phosphorus (^{32}P) or sulphur (^{35}S) are commonly used as tracers to determine the pattern of nutrient uptake. Whereas other workers have used one or the other of these isotopes to determine relative root activity (RRA), in this study they were used simultaneously for the first time.

A solution containing ^{32}P and ^{35}S was loaded into gelatin capsules in a method similar to that outlined by Goh et al. (1977) and Gillingham (1978). The major difference in the method was the manner in which the capsule was filled with radioactive tracer. A gun type mechanism was constructed which held the capsule while the needle of the ovijector gun penetrated it. Into each capsule was dispensed 1 ml of solution containing 5.8 µCi of ^{32}P and 7.3 µCi of ^{35}S.

On each of the pipe-mole and undrained plots, a transect of seven gelatin capsules spaced at 5 cm intervals was laid at the required treatment depth. These treatment depths were 20, 60, 110 and 170 mm. The depths were chosen to represent the soil sampling zones of 0 - 40, 40 - 80, 80 - 140 and 140 - 200 mm, respectively. Vertical holes to the required depth were made using a wooden template and a metal rod as described by Gillingham (1978). A frozen capsule was placed into each hole using long tweezers and guided to the bottom of the hole with a rod. Each hole was then backfilled with soil from the appropriate depth which had been removed from a pit nearby.

Between implacing the gelatin capsules and harvesting the pasture, soil cores from the relevant treatment depths were collected to determine the quantity of H_2PO_4-P and SO_4-S, according to the procedures outlined in Section 5.2.3.

The pasture was harvested approximately 10 - 14 days after isotope placement. Above the placement depths of 80, 110 and 170 mm all the herbage 150 mm on either side of the transect or 'hotline' was gathered using electric shears and a wooden quadrat. Above the 20 mm placement depth the area was divided into two regions; from the hotline to 75 mm and from 75 mm out to 150 mm. RRA values from these two regions were added to give the total value for the 0 - 40 mm zone.

In the laboratory, herbage samples were dissected into grasses and clover using long tweezers. After drying (60°C for 16 h) the samples were ground using a small electric coffee mill. Samples of ground herbage (0.15 g) were taken and digested according to the Kjeldahl procedure (Section 5.2.2). For scintillation counting, 1 ml aliquots of the digest were taken and transferred to vials containing scintillation cocktail (10 ml of Triton X100 – toluence 1 : 2 containing 4 g PPO and 0.1 g POPO per litre) (Patterson and Green, 1965). The liquid scintillation counter (Beckman LS-350) was set so that one channel would total the counts per minute due to the decay of ^{32}P (a setting of 720 - 1000) and another channel was given a window width from 30 - 720 to determine the counts per minute due to the decay of ^{35}S and low energy ^{32}P. A specific fraction of the counts of ^{32}P occurring in the 720 - 1000 region always falls below the 720 setting and by determining this fraction (0.39) it was possible to separate the counts in the 30 - 720 window into those due to emissions from ^{35}S and those due to emissions from ^{32}P. An external standard was used with an automatic quench control to ensure that all samples exhibited similar counting efficiencies.

Two isotope trials were laid down in 1983; the first in September and the second in December to determine the effect of drainage on the RRA during winter and spring.

5.2.5 Statistical analysis

The significance of differences in mean values of botanical composition between drainage treatments was determined using the t-test.

For the chemical composition of herbage and soil test data, with their greater sample space, variability was assessed from an analysis of variance based on the split-plot in time design followed by the determination of least significant difference (Little and Hills, 1972).

The significance of differences in relative root activity between drainage treatments was determined using the t-test, as outlined by Syers et al. (1984).

5.3 Results

5.3.1 Effect of mole drainage upon botanical composition

5.3.1.1 1982 - a dry year

In 1982, drainage did not significantly affect the botanical composition of the sward. The percentage of clover and weeds in the sward for each treatment, determined by dissection in the laboratory, appears in Fig. 5.1.

5.3.1.2 1983 - an average year

Following mob grazing in late July 1983 and set stocking throughout spring, it became noticeable in late spring and early summer that differences in the species composition were developing between the wet areas of the undrained plots and the drained plots. On the wet areas there was an obvious increase in the quantity of weeds, particularly buttercup which is tolerant of waterlogged conditions.

The results obtained from a point analysis carried out on 5 December, 1983 appear in Table 5.1. By far the greater part of the pasture sward was comprised of grasses, particularly perennial ryegrass. The preponderance of grasses masks any differences that may develop between

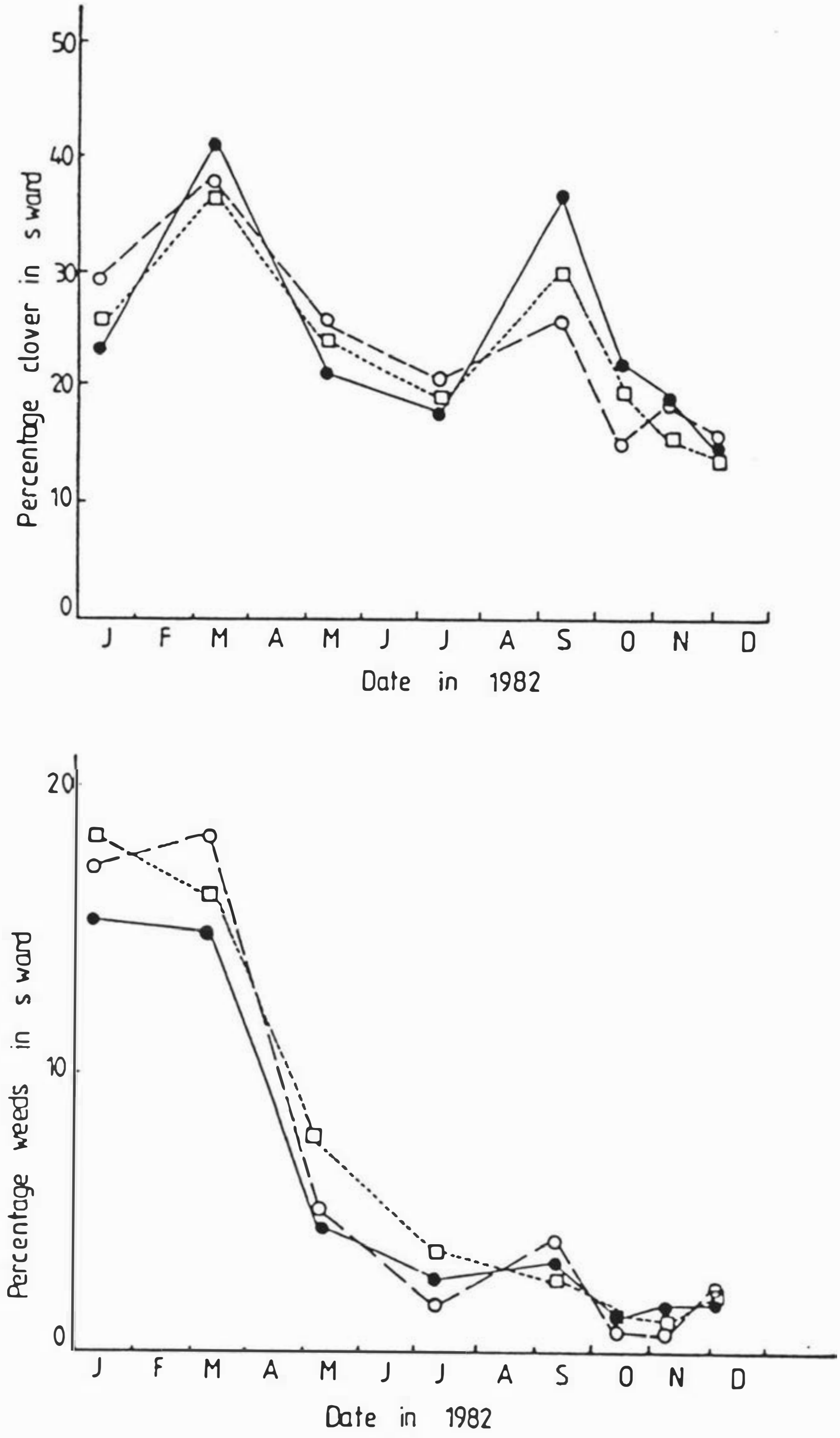


Figure 5.1 Clover and weed content of sward (expressed as a percentage) on pipe-mole (○--○), mole-mole (□···□) and undrained (●—●) plots measured by herbage dissection in 1982 .

Table 5.1 Pasture composition (expressed as a percentage) for drained and wet areas of undrained plots measured by the point analysis technique on the 5 December, 1983.

Mean values for a category followed by a different letter are significantly different at $P \leq 0.05$.

	Species						
Plots	Weeds	Buttercup	Ryegrass	Other Grasses	Clover	Bare Ground	Dead Material
Drained	4 a	0 a	61 a	12 a	12 a	2 a	9 a
Undrained	8 b	5 b	56 a	9 a	5 b	8 b	9 a

other species in the sward. This is illustrated in Table 5.1 where the differences in the quantities of weeds, buttercup and bare ground between the drained and wet areas of the undrained plots were not large in absolute terms. Nevertheless, there were significant ($P \leqslant 0.05$) differences in the incidence of some components of the sward between drained and undrained plots, with a 2-fold difference in the incidence of weeds and a 4-fold difference in the incidence of bare ground. There was also a large decrease ($P \leqslant 0.05$) in the incidence of buttercup, as well as a 2-fold increase ($P \leqslant 0.05$) in the incidence of clover when going from undrained to drained plots.

Results for the clover and weed component of the sward, as determined by herbage dissections carried out on samples collected from the pasture cages, are presented in Table 5.2. For all harvests except 7 November and 20 January, the percentage of clover on the drained plots was approximately equal to that on the wet areas of the undrained plots. However, towards the end of spring and in the middle of a mild summer, when conditions were favourable for good clover growth there was a significant ($P \leqslant 0.05$) difference in the percentage of clover between the wet areas of the undrained and the drained plots. For the January harvest there was approximately a 2-fold increase in the percentage of clover on the drained plots compared with the wet areas of the undrained plots.

Table 5.2 also shows that the sward on the wet areas of the undrained plots had a higher weed content than the sward on the drained plots. This difference was significant ($P \leqslant 0.05$) in both the November and January harvests. There was approximately 3 times the quantity of weeds in the sward on the wet areas compared with the drained plots. This is in good agreement with the results obtained by the point analysis method.

To determine whether or not the differences in species composition

Table 5.2 Clover and weed content of sward (expressed as a percentage) measured during spring and early summer of 1983/1984 by dissection.

Mean values of a category for a harvest followed by a different letter are significantly different at $P \leqslant 0.05$.

Date of harvest	Clover (%)			Weeds (%)		
	Pipe-mole	Mole-mole	Undrained	Pipe-mole	Mole-mole	Undrained
28 July	2 a	3 a	1 a	1 a	1 a	1 a
4 October	4 a	5 a	4 a	1 a	1 a	3 a
7 November	7 a	9 a	5 b	3 a	2 a	9 b
1 December	6 a	6 a	4 a	2 a	2 a	4 a
20 January	16 a	13 a	7 b	2 a	2 a	10 b

between drained and wet areas persisted, another point analysis was carried out in April 1984, the results of which appear in Table 5.3. By then, all differences between plots in the amount of clover and bare ground had disappeared. However, there was still approximately 3 times the incidence of weeds ($P \leqslant 0.05$) on the wet areas than on the drained plots.

5.3.2 Effect of drainage on the chemical composition

5.3.2.1 1982 - a dry year

In 1982, drainage had no significant effect on the concentrations of N, P or S in either grass or clover. The N, P and S content of pasture for the spring-summer period of 1982 is shown in Appendix B.

5.3.2.2 1983 - an average year

During the spring-summer of 1983/1984, differences in the chemical composition of herbage between drained plots and the wet areas began to develop. Chemical composition data for herbage harvested in this period appear in Fig. 5.2. The first differences are seen in the N and P content of clover samples harvested on the 4 October, 1983. Clover grown on the wet areas of the undrained plots had a significantly ($P \leqslant 0.05$) lower N and P content than did clover grown on the drained plots. For the October harvest there was no difference in the chemical composition of grasses sampled on the different drainage treatments.

One month later in November, there were quite pronounced differences in the chemical composition of herbage from the different treatments. The percentage of P in clover on the pipe-mole plots was 0.37 compared with 0.23 on the undrained plots. The percentage of N in clover on the pipe-mole plots was 4.97 compared with 3.68 on the undrained plot. These differences between drained and undrained plots in the levels of N and P

Table 5.3 Pasture composition (expressed as a percentage) for drained and wet areas of undrained plots measured by the point analysis technique on the 2 April, 1984.

Mean values for a category followed by a different letter are significantly different at $P \leqslant 0.05$.

	Species						
Plots	Weeds	Buttercup	Ryegrass	Other Grasses	Clover	Bare Ground	Dead Material
Drained	2 a	0 a	65 a	6 a	24 a	1 a	2 a
Undrained	6 b	1 a	64 a	5 a	22 a	1 a	1 a

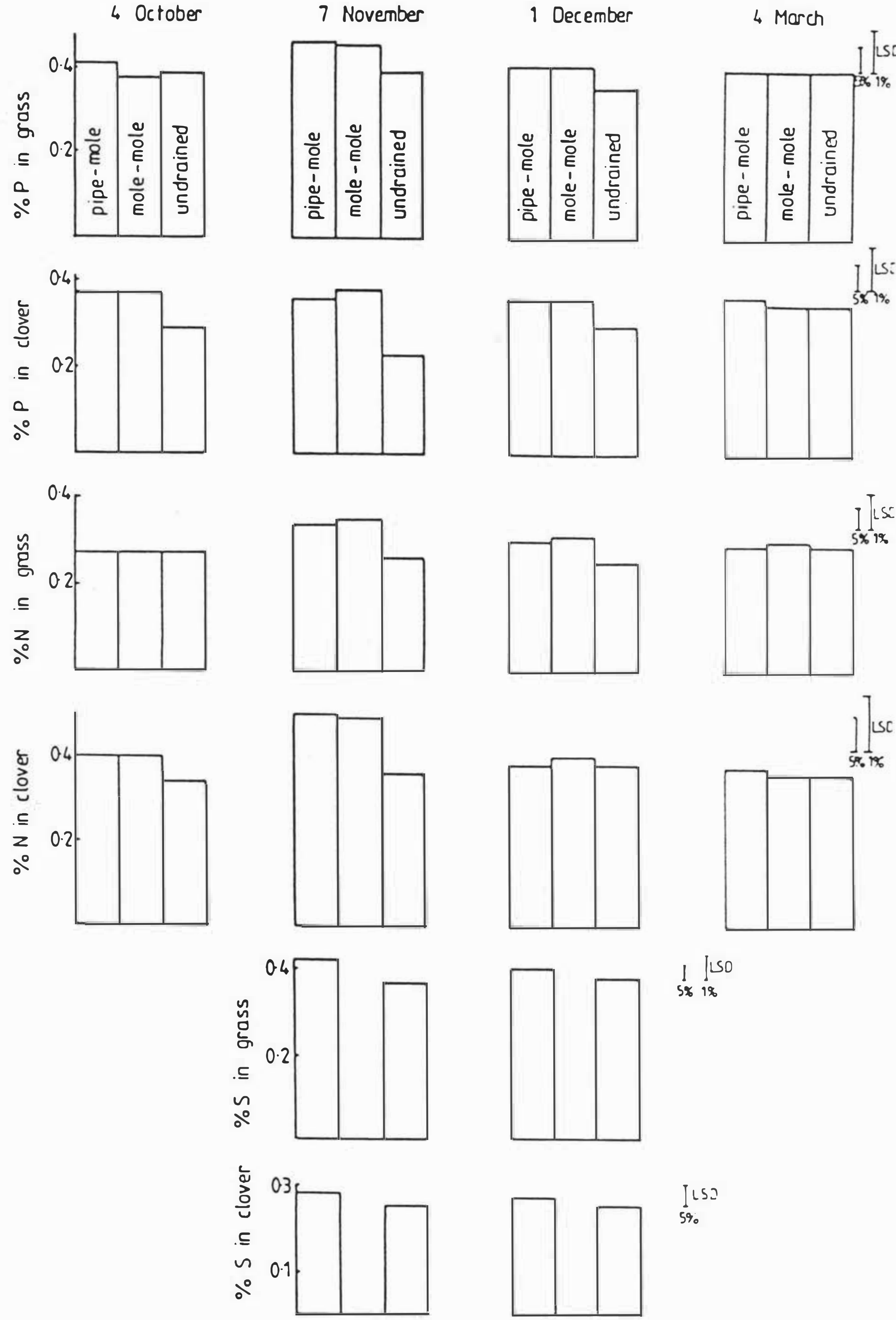


Figure 5.2 Percentage of N, P and S in grass and cover in the spring - summer period of 1983/1984. Least significant difference (LSD) at the 1% and 5% level .

in clover were highly significant ($P \leq 0.01$). The difference in S levels between clover grown on drained and wet areas was not significant.

For grass grown in November on the pipe-mole plots the levels of P, N and S were 0.47, 3.28 and 0.42, respectively, compared with the levels in grass on the undrained plots of 0.39, 2.75 and 0.37, respectively. The difference in the percentage of N in grass on the drained and undrained treatments was highly significant ($P \leq 0.01$), while the corresponding difference for P and S was significant at the $P \leq 0.05$ level.

Some of the significant differences in P, N and S contents observed for both clover and grass in November had disappeared by December. For clover there was no significant difference between drainage treatments in N or S levels, but the percentage of P present in clover sampled on the wet areas was still significantly lower ($P \leq 0.05$) than in clover sampled on drained plots. For grass there were no significant differences between treatments for S content. Grass on the drained plots still had a significantly ($P \leq 0.05$) higher N content than did grass on the undrained plots.

By the end of the summer of 1984 all significant differences in the chemical composition of herbage had disappeared.

5.3.3 Effect of drainage on soil nutrient status

5.3.3.1 1982 - a dry year

Although there were some marked seasonal fluctuations, particularly for NO_3-N and SO_4-S, in a dry year there were no significant differences in soil test values between drainage treatments. Soil test data for SO_4-S, H_2PO_4-P, NO_3-N, NH_4-N and pH are presented in Fig. 5.3.

5.3.3.2 1983 - an average year

As for 1982, there were seasonal fluctuations but no

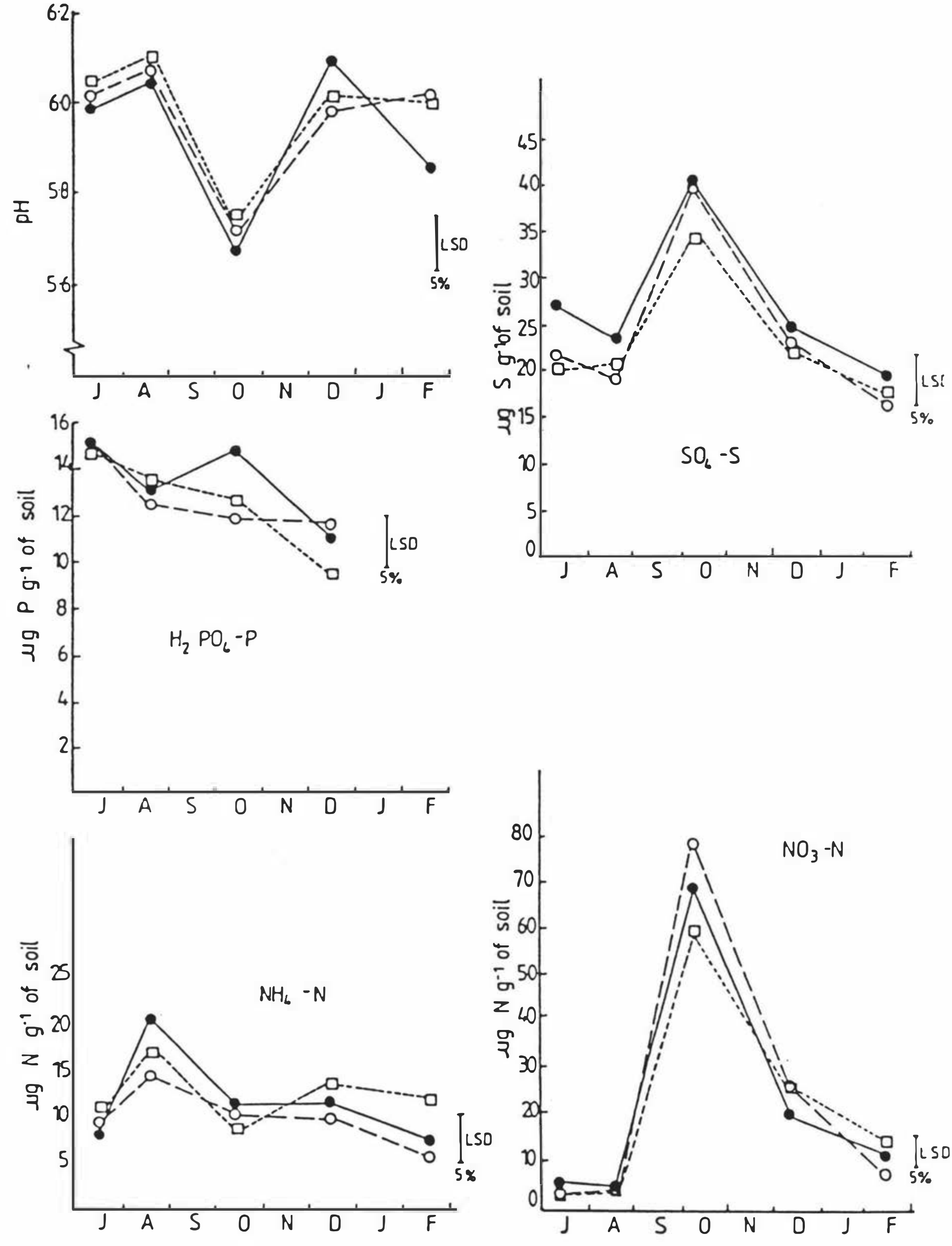


Figure 5.3 Soil test data for pipe-mole (○--○) mole-mole (□···□) and undrained (●—●) plots in 1982. Least significant difference (LSD) at the 5% level.

significant differences in soil test values between drainage treatments. Soil test data obtained in 1983 are presented in Fig. 5.4. Even for a year of average rainfall, in which the watertable over the winter-spring period was considerably higher on the undrained soil than on drained, the soil test values for all plots were approximately the same.

5.3.4 Effect of drainage on the plant root system

5.3.4.1 Relative root activity during winter

In winter, drainage had an effect on the relative root activity (RRA) in the 40 - 80 mm zone. RRA values calculated at the end of the winter of 1983 are shown in Fig. 5.5. In the region 40 - 80 mm both grass and clover root activity for SO_4-S on the drained plots was significantly ($P \leq 0.05$) greater than on the undrained plots. Likewise the root activity of grass for H_2PO_4-P was significantly ($P \leq 0.01$) greater on the drained plots. Comparison of RRA values for this zone in Fig. 5.5 show that the difference between drained and undrained plots was more pronounced for SO_4-S (with an average difference in RRA for both grass and clover of 12%) than for H_2PO_4-P (where the difference in RRA was approximately 7%). Soil sampling at the time of the trial (Table 5.4) showed that there was no significant difference in H_2PO_4-P and SO_4-S levels between drained and undrained plots in the 0 - 80 mm zone, the region of greatest nutrient uptake.

5.3.4.2 Relative root activity during spring

Unlike the winter trial, root activity in spring was not so confined to the top of the profile, but important contributions to the plant's nutrient requirements were made by roots in the 160 - 200 mm zone. RRA values for both grass and clover for H_2PO_4- P and SO_4-S, as measured on drained and undrained plots at the end of the spring in 1983, are presented in Fig. 5.6.

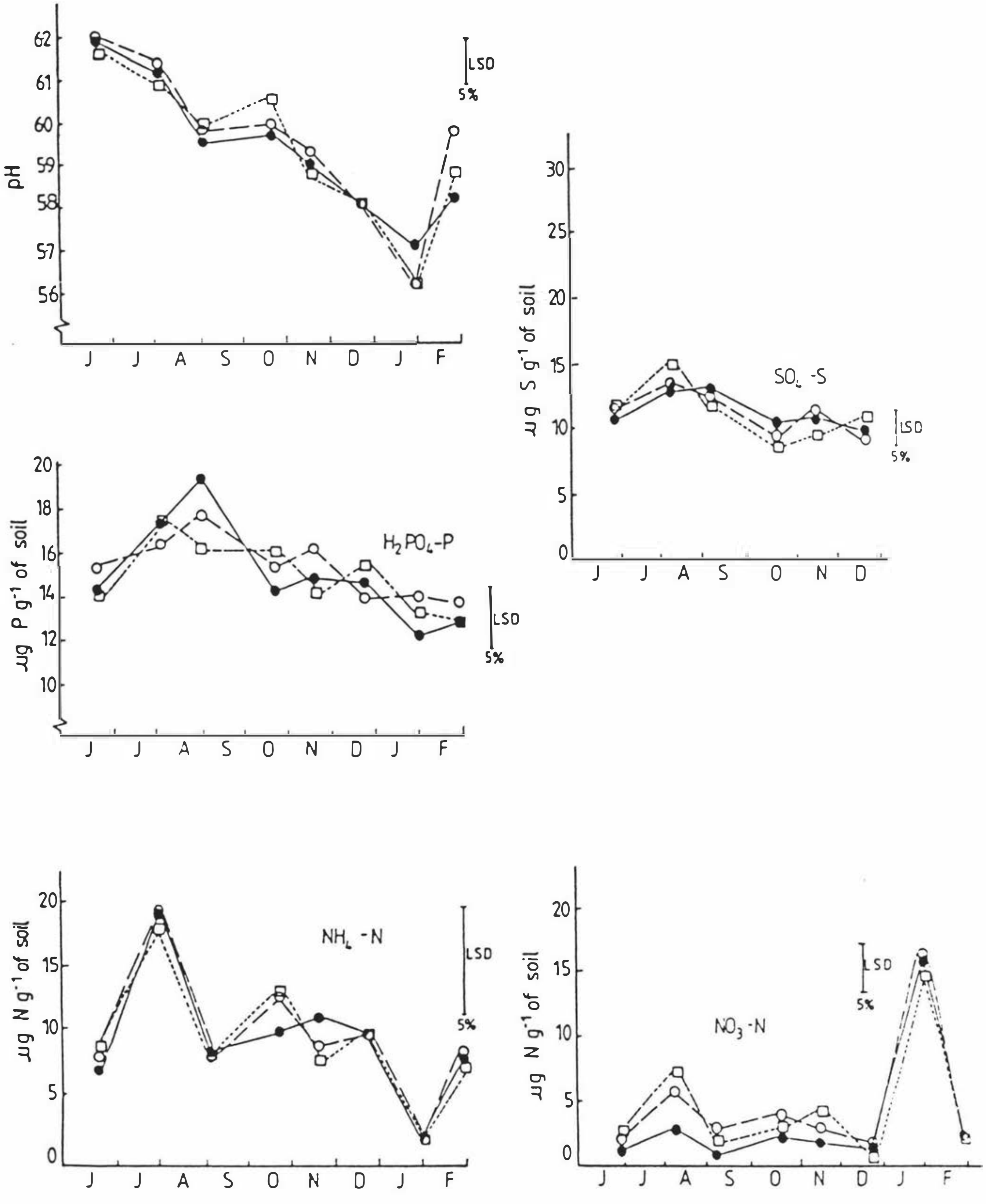


Figure 5.4 Soil test data for pipe-mole (○--○), mole-mole (□···□) and undrained (●——●) plots in 1983. Least significant difference (LSD) at the 5% level .

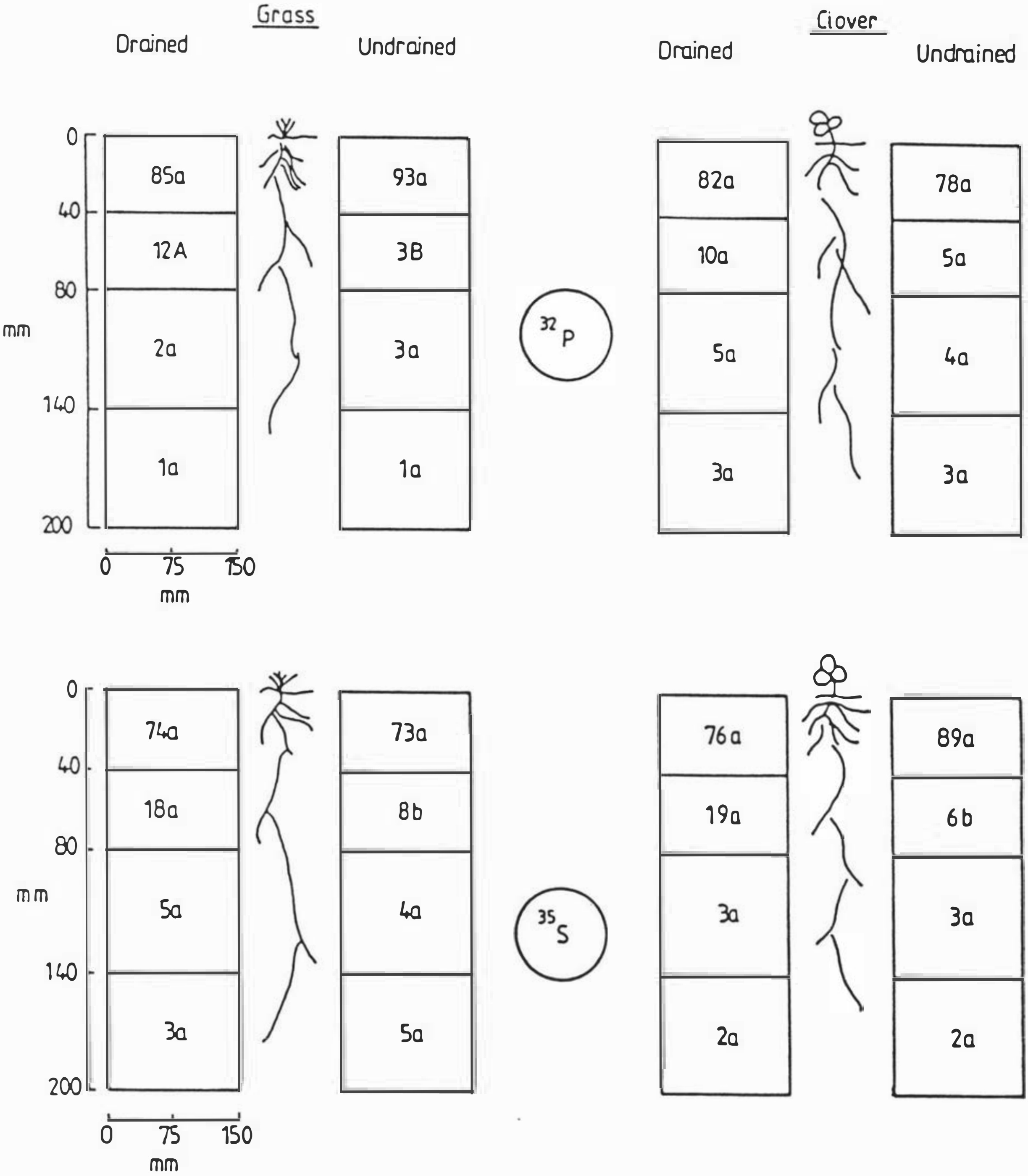


Figure 5.5 Relative root activity measured in September, 1983. Mean values for uptake of a tracer by a species from a particular zone followed by a different lower case letter are significantly different at $P \leqslant 0.05$. Mean values followed by different upper case letters are significantly different at $P \leqslant 0.01$.

Table 5.4 Soil test data obtained during the September and December isotope trials (1983).

Mean values at a particular depth for a nutrient followed by a different letter are significantly different at $P \leqslant 0.05$.

	September			
	H_2PO_4-P	(μg P g^{-1} of soil)	SO_4-S	(μg S g^{-1} of soil)
Depth (mm)	Drained plots	Undrained plots	Drained plots	Undrained plots
0- 40	16.3 a	19.0 a	8.2 a	9.5 a
40- 80	12.3a	14.0 a	6.0 a	7.6 a
80-140	8.6 a	12.1 a	6.0 a	9.3 b
140-200	8.1 a	7.3 a	7.6 a	11.8 b
	December			
0- 40	8.3 a	10.0 a	15.5 a	16.0 a
40- 80	7.0 a	10.0 a	12.1 a	14.0 a
80-140	7.0 a	10.2 a	9.3 a	9.6 a
140-200	7.6 a	11.1 a	7.0 a	8.0 a

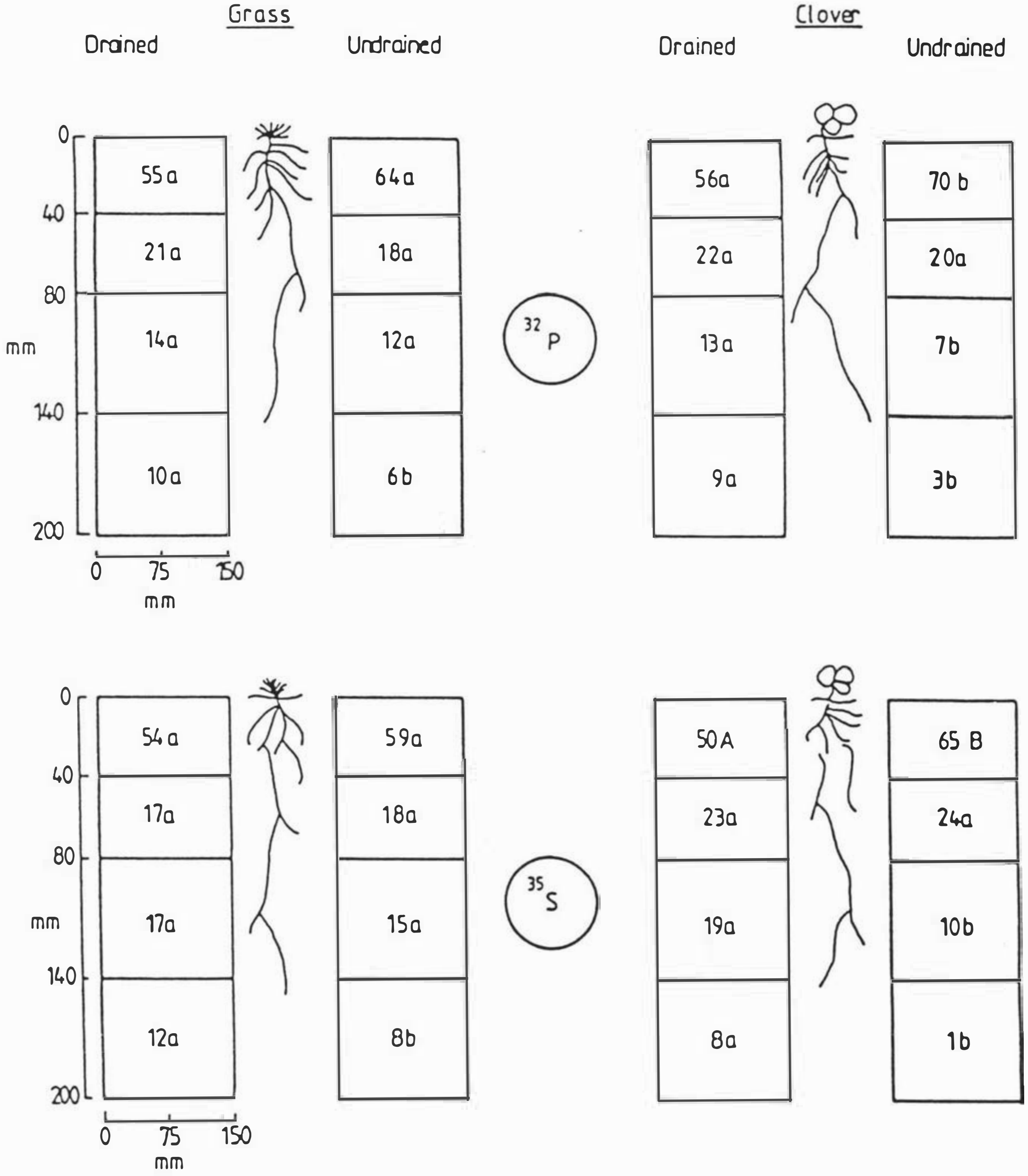


Figure 5.6 Relative root activity measured in December, 1983. Mean values for uptake of a tracer by a species from a particular zone followed by a different lower case letter are significantly different at $P \leq 0.05$. Mean values followed by different upper case letters are significantly different at $P \leq 0.01$.

Drainage continued throughout spring to have an effect on root distribution. RRA was greater in the 0 - 40 mm zone in the undrained plots than in the drained plots, the magnitude of this difference being approximately 10%. The differences were significant at either $P \leqslant 0.05$ or $P \leqslant 0.01$, as shown in Fig. 5.6.

For grass, RRA on the drained plots between the depths of 160 and 200 mm for both H_2PO_4-P and SO_4-S was significantly ($P \leqslant 0.05$) greater than for the undrained plots; for clover the RRA in the drained plots was significantly ($P \leqslant 0.05$) greater in the 80 - 160 mm zone as well as in the 160 - 200 mm zone. Table 5.4 shows that for the December trial there were no significant differences in the amount of plant available H_2PO_4-P and SO_4-S between drained and undrained plots.

Drainage did not affect the lateral spread of either the grass or clover root system in the surface soil. When RRA values for the region 75 mm from the hotline out to 150 mm from the hotline were tested no significant differences between drained and undrained plots were found for either grass or clover.

5.4 Discussion

The results presented in Section 5.3.1 show the important effect that drainage may have on botanical composition. In a dry year, when the watertable level was usually well down the soil profile and unsafe grazing days were few in number, pasture composition was the same on drained and undrained soil. As would be expected in such years, drainage was of little benefit in terms of improving the botanical composition of the sward. However, if during a year of average rainfall, grazing is allowed on an unsafe grazing day, then the resultant treading damage is likely to be detrimental to the botanical composition of the sward.

However, if during a year of average rainfall grazing is allowed on an unsafe grazing day, then the resultant treading damage is likely to be detrimental to the botanical composition of the sward. Although differences in species composition may be small and are unlikely to be manifest until late spring-early summer, the differences can persist well into summer and the poorer quality species may still be present the following autumn. The net result of this could be a gradual deterioration in the quality of the pasture sward on a poorly drained soil.

The findings in this study concerning changes in botanical composition induced by treading damage are in agreement with the findings of other workers (Hopewell, 1954). Curll and Wilkins (1983) report that the percentage of bare ground was increased by treading and that treading also reduced the percentage of clover in autumn. Brown and Evans (1973) in a review of the work of D.B. Edmond also state that clover was found to be more susceptible to treading damage than ryegrass which is in agreement with the reduction in the incidence of clover on the undrained plots observed in this study. Discussing aspects of treading damage Sears (1947) stated "... in excess this can open up a sward and pug the soil so that pasture growth is seriously impaired and weeds obtain a start ...".

Differences in the elemental composition of grass and clover first became apparent in the middle of the spring of 1983. These differences were fairly short lived, as by the beginning of the summer of 1983 some of these differences no longer existed and by the end of the summer 1983/1984 all differences had disappeared. However, at the time of maximum pasture growth in late October/early November, considerable differences in the levels of the important nutrients N, P and S in both grass and clover existed between drained and undrained plots. Grass and clover grown on the wet areas contained significantly less N, P and S than did herbage grown on the drained plots. In late October/ early November this would have equated to an increase on drained plots over wet areas of very approximately 5 kg ha^{-1} of P, 39 kg ha^{-1} of N, and 4 kg ha^{-1} of S.

Whether the poorer uptake of nutrients on the wet areas was attributable to the impaired performance of shoots or roots following grazing is not clear. Damage to the tissue of the shoots, incurred during grazing, may have been responsible for lower levels of nutrients in herbage on the wet areas. It is also possible that damage to the root network at the soil surface (Curll and Wilkins, 1983; Langlands and Bennett, 1973) was the primary cause of reduced uptake on the wet areas.

Another possible reason for the higher nutrient levels in the herbage on the drained plots was the greater dung return to these plots as reported in Section 4.3.2.2. Soil testing did not reveal differences in nutrient availability between drained and undrained plots but this may be because differences would not begin to show in soil test values until some time after sampling on the research area ceased. Also, herbage on the undrained plots was old and long whereas the herbage on the drained plots was young and fast growing, and therefore more likely to have higher nutrient levels.

The most striking feature of the isotope data is that most of the plant's nutrient requirements are met by root extraction close to the soil surface. Many other workers have made similar observations (Jackman and Mouat, 1972; Uyo, 1974; Syers et al., 1984). In the cold winter months, root growth is minimal (McWilliam, 1978) so that nearly all of the plant's nutrient requirements are supplied by roots from the top 80 mm of soil. Plant roots have no necessity to explore the soil volumes deeper in the profile, as they might need to for nutrients if plant growth rates were higher, or for water reserves if the plant was under moisture stress. Soil test values for the profile showed that the reason plant roots are more active in the 40 - 80 mm zone on the drained plots cannot be attributed to greater nutrient availability in this region on the drained soil.

There are two likely reasons why the plant root network was inhibited from extensively ramifying deeper than 40 mm on the undrained soil. Firstly, the high watertable which was present for many days may have restricted root activity to the surface zone. Plant roots cannot function as well below the watertable as aerobic respiration is often curtailed (Russell, 1977). Secondly, unsafe grazing in the middle of winter may have so damaged the shoots and roots of the plant that they were unable to properly support the root system. If the shoots are damaged then the flow of synthates and hence respiratory substrate to the roots may be restricted, and root activity would therefore be limited (Harris, 1978). It has also been reported (Curll and Wilkins, 1983) that treading by grazing animals can reduce root weight close to the soil surface. If roots close to the surface had been damaged during grazing then much of the root activity may have been confined to replacing the damaged surface soil roots. Proliferation and replacement at the surface would have been at the expense of activity deeper within the profile.

Lowering the watertable with subsurface drainage encouraged roots to proliferate further down into the profile, even though this zone of enhanced activity may extend for only another 40 mm or so over the cold winter period.

Two other features of the plant root system are evident in Fig. 5.5. They are the similarity in the root activity pattern of grasses and clovers in winter, and the greater contribution to the SO_4-S requirements of the plant from roots deeper within the profile than is the case for H_2PO_4-P. These observations are consistent with results obtained during preliminary trials carried out in 1981 and 1982, and results presented by Brash (1973) and Gregg (1976).

In spring, significant differences developed between drained and undrained plots in the amount of root activity in the top 40 mm of the soil profile. On the undrained plot, a greater proportion of the root activity was confined to this surface zone than was the case for the drained plot. This difference can probably be attributed to the high watertable level on the undrained plot and the inability of the shoots and roots damaged during unsafe grazing to encourage root activity at depth.

Whereas the deeper portions of the root system had been relatively inactive over the winter months, with the greater spring growth rates the root network becomes active at depth, extending down into and exploring deeper soil zones for nutrients (Davidson, 1978). For the winter trial, RRA was significantly greater in the 40 - 80 mm zone on the drained plots than for the undrained plots and approximately the same below a depth of 80 mm. In contrast, during spring, RRA was approximately equal for both treatments in the 40 - 80 mm zone, but was significantly higher on the drained plots in the zone 80 - 200 mm. These differences in the relative root activity between drained and undrained soil and differences between seasons can be explained by considering the direct and indirect effect the watertable level had on plant root development as discussed above.

An interesting feature of the comparison between the plant root systems on drained and undrained plots is that the root system of clover seems to be more affected by drainage than does that of grass. The difference between drainage treatments in RRA for H_2PO_4-P below 80 mm for clover was 12%, compared with 6% for grass, and similarly the difference in activity for SO_4-S was 16% for clover compared with 6% for grass.

This difference between grass and clover can be attributed to the ability of grass to recover more quickly than clover following a period of waterlogging and/or unsafe grazing (Edmond, 1966; Gradwell, 1969). Following a winter of relative inactivity for all plant roots, grass roots which are more tolerant of wet conditions and treading damage, can quickly proliferate and explore deeper soil volumes. The observation that the root network of clover is more adversly affected by waterlogging and/or treading damage is consistent with the data presented in Sections 5.3.1.2 and 5.3.2.2 which showed that following grazing the percentage of clover present in the sward decreased. Also, the reduction in the levels of N, P and S observed when comparing herbage grown on the drained plots with that grown on the wet areas was more marked for clover than grass.

As discussed above, the relationship between the shoots and roots is unclear. It is not possible to state whether the part treading damage had in lowering nutrient levels in herbage on the undrained plots was because the damaged shoots could not properly support the root system as it foraged for nutrients, or conversely, if it was that the damaged root network could not supply the nutrients needed by the shoots to recover from the damage incurred during unsafe grazing. Likewise, it is not possible to conclude whether the observed ability of grass to recover from treading damage more quickly than clover was because of greater resilience in its shoots or because of a more competitive or extensive root network or a combination of these two factors.

Plant roots that penetrate deeper into the soil profile can obtain water there and hence improve the plant's water relations during times of moisture stress (Grable, 1966; Van de Goor, 1972). Neutron moisture meter data for the mild summer of 1984, presented in Fig. 5.7 show that more water was being removed from depth on the drained plots than on the undrained plots. However, this was to be expected as at 'field capacity' the drained plots had about 20 mm less water for plant uptake above mole depth than did undrained plots (see Section 7.3 and Scotter, 1979a). Therefore, plant roots on the drained plots have to meet the evaporative demand placed on the plant using water extracted from deeper within the profile. Had the summer of 1984 been drier, the root pattern established at depth on the drained plot may have helped the pasture produce for longer periods than the shallower rooting pasture on the undrained plots.

It is sometimes claimed that it is possible to "overdrain" a soil and therefore subject pasture to greater stress in dry periods than that experienced by pasture on undrained soil. Because the summer of 1983/1984 was not dry, it is not possible to state that drainage actually increased pasture tolerance of drought conditions by encouraging a deeper rooting pattern. But as discussed, the neutron probe data suggest that water extraction by the plant roots was greater at depth on the drained plot compared to the undrained. It might also be remembered, that there is only 20 mm more water available in the undrained profile and this would quickly be used in the high evaporative demand (up to 6 mm d^{-1}) associated with a hot summer.

The above discussion serves to highlight the important effects of drainage on the plant root system. Drainage was of slight benefit to the root during the winter months of relative inactivity. In spring however, plant roots on the drained plots had an advantage over the roots in the undrained soil, in that they were able to explore a greater soil volume for nutrients. This was more pronounced for clover than grass.

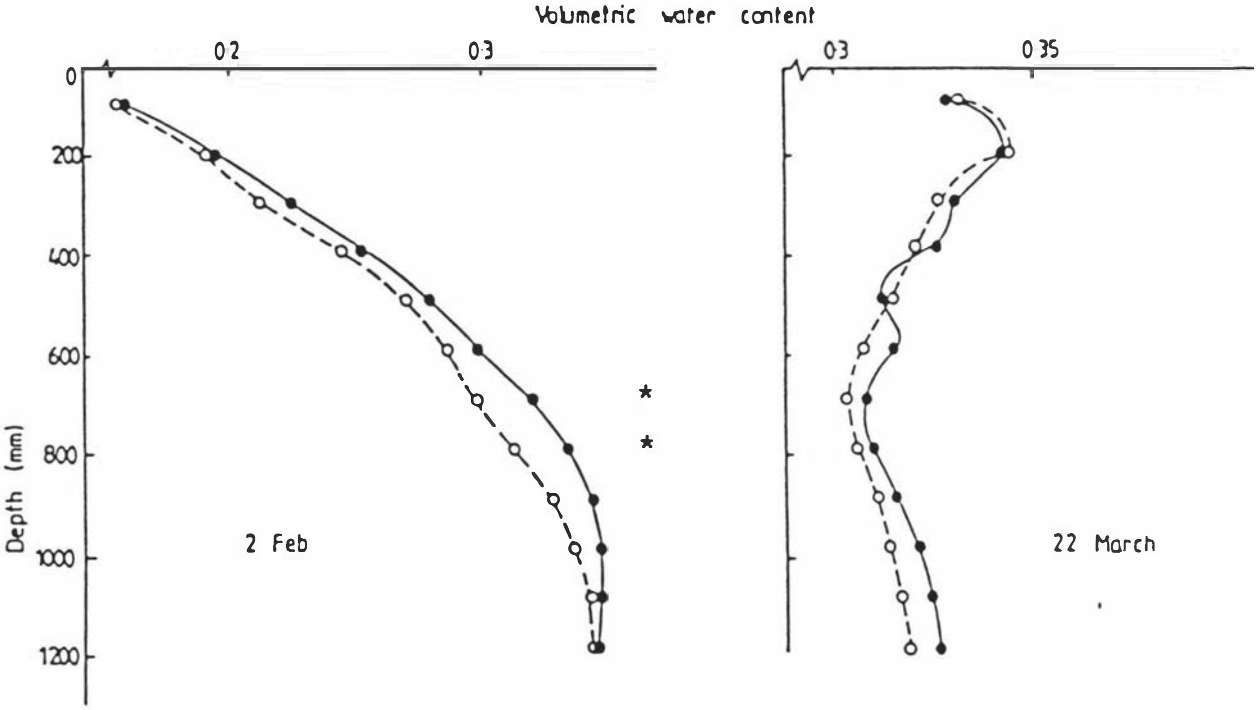


Figure 5.7 Volumetric water content of pipe-mole (○--○) and undrained (●—●) soil profiles on two occasions in the summer of 1984. For depths where a (*) appears the difference between the mean values for the drained and undrained plots was significant at $P \leqslant 0.05$.

In effect, drainage was minimising any disadvantage the plant might suffer due to a high watertable level and/or damage done to the shoots and roots during unsafe grazing.

5.5 Conclusions

The following conclusions may be drawn:

i) Drainage improved the botanical composition of an intensively grazed sward by minimizing the adverse effects of treading damage. At the end of spring in an average year there, was a reduction in the incidence of weeds and bare ground and an increase in the incidence of clover on the drained plots relative to the undrained plots.

ii) At the end of spring in an average year, the N, P and S content in grass and clover was lower on the undrained than on the drained plots. A number of factors probably contributed to this including greater treading damage and lower dung return on the undrained plots and the younger nature of the sward on the drained plots.

iii) Drainage allowed plant roots to utilise nutrients at greater depths within the soil profile in both winter and spring.

iv) Clover seemed to be more adversely affected by the grazing of waterlogged soils than did grass.

CHAPTER 6

CHAPTER 6

THE EFFECT OF DRAINAGE ON SOIL TEMPERATURE AND AERATION

6.1 Introduction

In the preceding two chapters some of the effects of drainage on pasture have been discussed. It was concluded that for a year of average rainfall, drainage was beneficial in that it increased pasture utilisation by grazing sheep, enhanced regrowth rates during spring, and improved certain aspects of the sward, such as botanical composition, N, P and S levels within the herbage and root distribution.

In the last two chapters many of the benefits of drainage were attributed to the ameliorating effect drainage has on the interaction between the hoof of the grazing animal, the wet soil and the plant. However, in Chapter 1 it was claimed that some of the benefits of drainage are the result of increased soil temperatures and soil aeration induced by drainage.

A direct effect of low soil temperatures is that the growth of roots will decrease, limiting the absorbing surface for uptake of nutrients and water (Hillel, 1982). Soil temperature influences plant growth indirectly by its effect on such factors as the availability of nutrients in the soil, soil moisture relations, and water uptake. Low soil temperatures will decelerate the decomposition of organic matter so that lower amounts of nutrients become available. Nitrogen in particular is affected (Wesseling, 1974).

The replacement of air by water in the soil pores through waterlogging will result in an increased specific heat of the soil, water requiring approximately 1000 times more heat to raise its temperature than an equivalent volume of air. Consequently, many soil physics and drainage books suggest a link between drainage and soil temperature in spring, e.g. (Baver et al., 1972; van Beers, 1972; Marshall and Holmes, 1979). Bowler (1980) claims: 'The effect that good drainage has on the warming up of soils in the early spring and the consequent growth responses in pasture and spring sown crops is one of its greatest advantages'.

However, despite the unequivocal statements referred to above, it is difficult to find data to support them, as Wesseling (1974) observes. Feddes (1972) found seedbed temperatures were raised about 1°C by drainage, but Trafford and Rycroft (1973) reported drainage of a heavy clay had no measurable effect on seedbed temperatures. Also soil temperatures measured at 12 and 20 mm depths under pasture by Scott (1963) gave no confirmation to the assertion that drained soils warm up more rapidly. Apart from the work of Scott (1963) no data seem to have been published showing the effect on soil temperature of drainage under pasture.

Although the depth of the watertable has no direct influence on pasture growth, it largely determines the soil water content and so has a bearing on soil aeration and the thermal properties of soils. Therefore in this Chapter measurements of spring soil temperatures under pasture with and without drainage is described. The resulting data and values of the thermal properties of saturated and drained soil cores from the field site are used in a simulation of the effects of drainage on soil temperature. There is also a discussion of the literature concerning the effect drainage is likely to have on soil aeration.

6.2 Materials and Methods

Prior to winter and spring of 1983, twelve mercury-in-glass soil temperature thermometers were placed at 100 mm depth on the Keebles site. Six thermometers were placed in the three undrained plots and the other six in the pipe-mole drained plots. The thermometers were read every few days, usually between 1000 and 1400 hours.

During August and early September of 1984, four thermistor thermometers were used to measure soil temperature at 50 mm depth, two in an undrained plot and two in an adjacent drained plot. Temperatures were monitored each minute and daily maximum, minimum and mean values (and also sometimes hourly mean values) were logged. On both plots watertable levels were measured in the two nearest observation wells.

Laboratory measurements were made (jointly with D.R. Scotter) of thermal diffusivity on intact soil cores at two matric potentials corresponding to a drained and undrained profile. Measurements were made firstly at the equilibrium matric potential which would be reached when the watertable was at mole-depth (i.e., -4.5 kPa at the soil surface), and secondly at a matric potential of zero, when the soil was effectively saturated. The results obtained and a discussion of the physics involved appear in Appendix C.

6.3 Results and Discussion

6.3.1 Effect of drainage on soil temperature

6.3.1.1 Soil temperature data

At no time was a significant difference in soil temperature at 100 mm between the drained and undrained plots measured, despite the pronounced effect drainage had on the watertable levels (Fig. 3.4) and gravimetric water contents (Fig. 3.11). In Fig. 6.1 are shown the

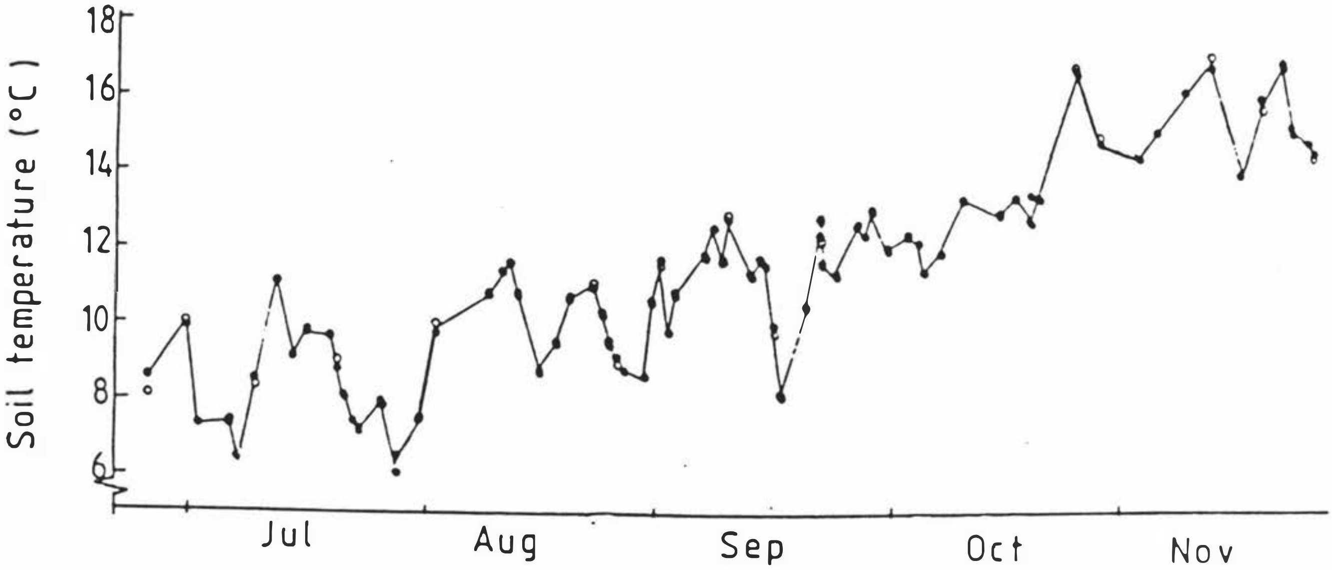


Figure 6.1 Soil temperatures at 100 mm depth on drained (○) and undrained (●) plots in 1983 .

measured temperatures in the drained and undrained plots during the winter and spring of 1983. Agreement between replicate thermometers was good, with a typical standard deviation of 0.2°C.

While the data in Fig. 6.1 show that day-time temperatures at 100 mm depth were unaffected by drainage, the possibility remained that drainage affected the magnitude of the diurnal temperature oscillations nearer the surface. Data relating to this are shown in Fig. 6.2 where soil temperatures at 50 mm are depicted. The difference between duplicate temperature measurements was typically about 0.2°C, but on a few occasions ranged up to 0.8°C. Such differences were probably largely due to local variations in plant cover. Generally differences between drained and undrained plots in maximum, minimum and mean temperatures were negligible, being of similar magnitude to the differences between duplicate measurements. Again this was despite very different watertable levels in drained and undrained plots, as shown in Fig. 6.2.

6.3.1.2 Discussion of soil temperature and drainage

The reasons why drainage has no apparent effect on soil temperature warrant discussion. There are two reasons commonly advanced for drainage leading to warmer soil in spring. These are, firstly, its effect on evaporation and secondly, its effect on soil heat capacity (c_v).

If drainage affects the evapotranspiration rate, it will inevitably affect the other ways in which the incoming net radiation is dissipated, including the soil heat flux. For example, if drainage expedites the drying of the surface of a seedbed, evaporation will be reduced and consequently the soil heat flux and soil temperature will be increased. Van Duin (1963) concludes that this is the major mechanism by which drainage affects seedbed temperature.

However, the evapotranspiration rate from full-cover pasture (leaf area index over about 2) free of water stress is determined almost

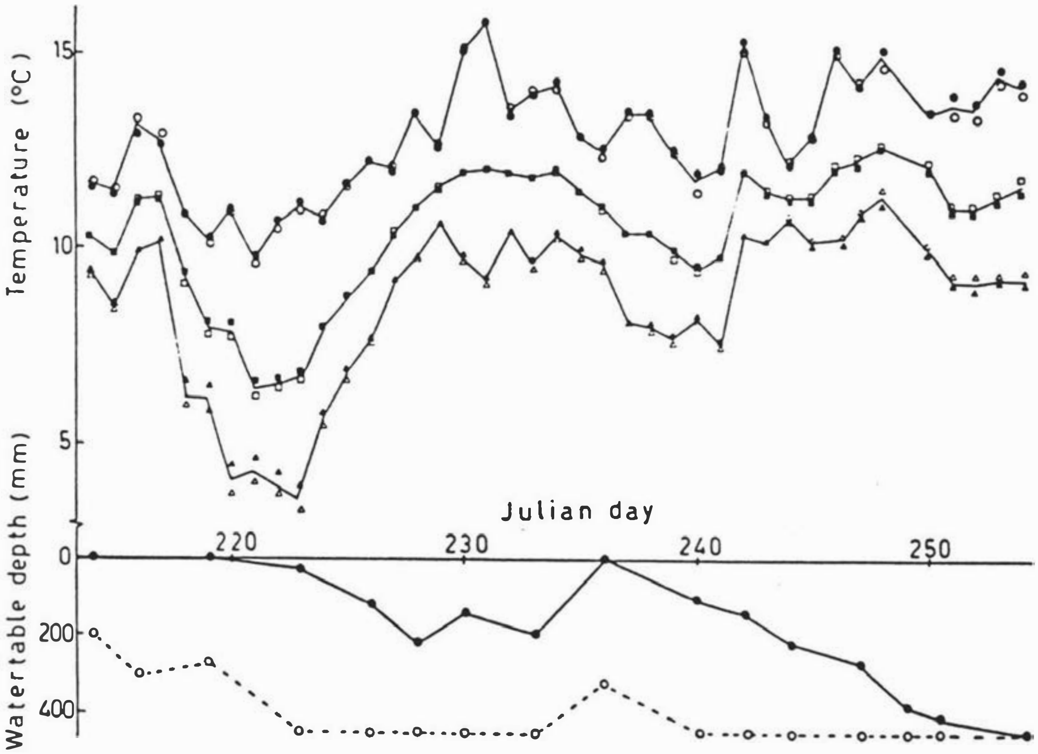


Figure 6.2 Watertable depths and daily maximum (●,○), mean (■,□) and minimum (▲,△) soil temperatures at 50 mm depth from 1 August to 10 September, 1984. Open symbols are for the drained plot and closed symbols for the undrained plot. If the watertable was deeper than 450 mm it was assigned a value of 450 mm .

completely by climatic conditions (Johns and Lazenby, 1973; Green **et al.**, 1984). It is thus independent of any differences in soil water content induced by drainage. Further, it was observed that the soil surface under pasture on both drained and undrained plots remained moist throughout winter and early spring. This meant that even if the leaf area index had been reduced by heavy grazing to less than 2, the evapotranspiration rate would still have been the same on both drained and undrained plots. This is because a moist or saturated soil surface loses water at a similar rate to short grass (Hillel, 1982). It can therefore be concluded with some confidence that evapotranspiration of pasture during winter and spring is not affected by drainage and therefore the soil heat flux is not likely to be affected either.

Next we need to consider how differences, induced by drainage, in soil thermal properties such as heat capacity, affect soil temperature, given the same heat flux at the surface. This is done in the next section.

6.3.1.3 Simulations of soil temperature

The major oscillations in soil surface heat flux are in response to diurnal and annual changes in solar radiation, although there is also the effect of meso-scale weather patterns with a period of several days, as can be seen in Fig. 6.1 and 6.2. Here we consider only the diurnal and annual cycles. Both these cycles are often idealised using the simple analytical solution for heat conduction into uniform soil with a sinusoidally varying heat flux at the soil surface. However,for our purposes this is not very satisfactory. For the annual oscillations, which have a damping depth of about 2 m, only the top 0.4 m is affected by drainage, so it is not reasonable to assume uniform thermal properties throughout the soil profile. This is not so much of a problem for the diurnal oscillations, for which the damping depth is about 0.1 m. But the diurnal surface soil heat flux is not well described by a simple sine wave on a clear day (see for example Fig. 33 on page 112 of Sellers, 1965). Analytical solutions for a layered soil (van Wijk and Derksen, 1966) and for a more realistic diurnal surface heat flux (Carslaw and Jaeger, 1959) have been published, but it was found simpler to use a finite difference solution of the one-dimensional diffusion equation. The solution used was that of de Wit and van Keulen (1975), except that a microcomputer and BASIC were used instead of a mainframe computer and CSMP.

For the annual oscillations, the soil heat flux density at the surface (f) was described by

$$f = F \sin (\omega t) \qquad (6.1)$$

where F is the amplitude of the oscillations and ω their angular velocity (1.99×10^{-7} s^{-1}). For soil with uniform thermal properties, it follows from equation (13) on page 76 of Carslaw and Jaeger (1959) that

$$F = A_x K_h \omega^{\frac{1}{2}} \exp [x(\omega/2 \kappa)^{\frac{1}{2}}]/\kappa^{\frac{1}{2}} \qquad (6.2)$$

where K_h is the thermal conductivity, κ is the thermal diffusivity (equal to K_h/c_v) and A_x is the amplitude of the temperature oscillations at depth x. Long-term soil temperature records for Palmerston North show a mean temperature of 13.9°C and an annual amplitude of 5.5°C at 300 mm depth. Using this value for A_x and letting K_h equal 1.1 W m^{-1} K^{-1} and κ equal 3.6×10^{-4} m^2 s^{-1} (Appendix C), we find from equation (6.2) that F equals 5.3 W m^{-2}.

The simulated soil temperature data shown in Fig. 6.3 were obtained using equation (6.1) as the boundary condition for both drained and undrained soil. Values for c_v and K_h were measured in the laboratory as described in Appendix C. For the drained soil, and for the undrained soil below 0.4 m depth, c_v was taken as 3.1 MJ m^{-3} K^{-1} and K_h as 1.1 W m^{-1} K^{-1}. For the top 0.4 m of undrained soil, c_v was taken as 3.3 MJ m^{-3} K^{-1} and K_h as 1.2 W m^{-1} K^{-1}. Of course in reality both c_v and K_h

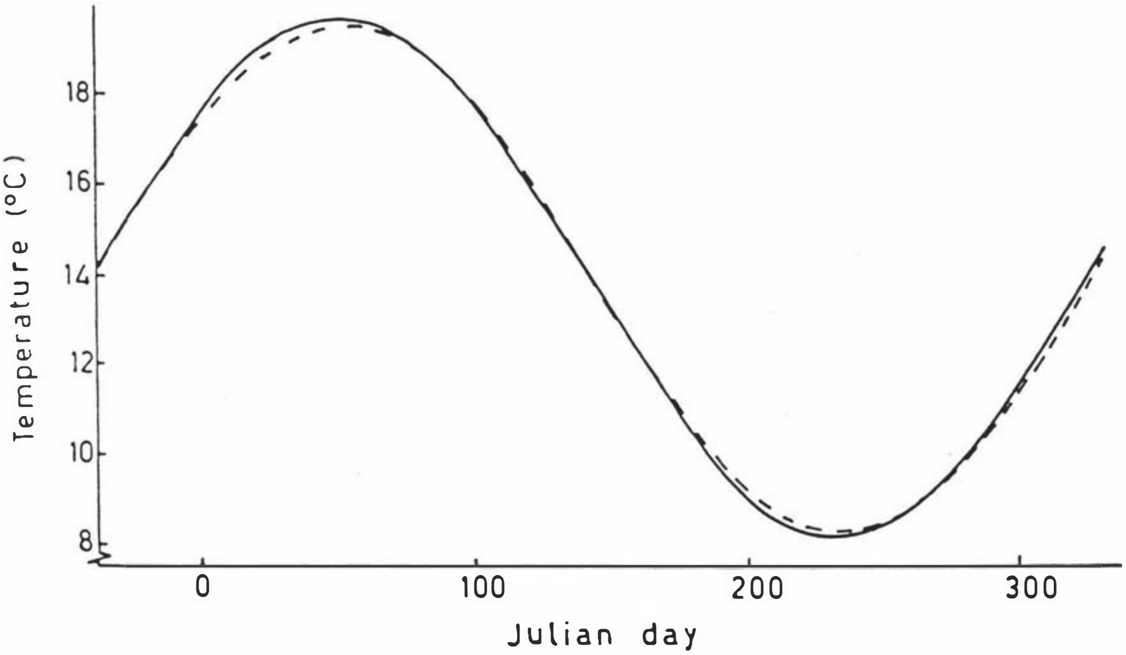


Figure 6.3 The simulated annual temperature cycle at 200 mm depth in drained (——) and undrained (- - —) soil .

will change seasonally with soil water content, but the assumptions made allow the effect of drainage on winter and spring soil temperatures to be estimated. The simulation shows the drained soil to be only 0.2°C warmer than the undrained soil in spring. This difference is equal to the standard deviation for replicate temperature measurements in the field, and helps explain why differences between drained and undrained plots could not be found in 1983.

Due to the shallow damping depth of diurnal temperature oscillations, they are more likely to be affected by drainage than are seasonal temperature changes. To simulate diurnal oscillations a realistic surface flux density boundary condition is needed. To obtain this, hourly soil temperature data from 50 mm depth for a number of days in early September were examined, and data for a mostly sunny day with similar maxima and minima to the preceding and following days were selected and are plotted in Fig. 6.4. It follows from equation (14) on page 77 of Carslaw and Jaeger (1959) that the soil heat flux density at the surface on a clear day near the equinox can be described by

$$\begin{aligned} f &= -b, \quad 2n\pi/\omega<t<(2n+1)\pi/\omega, \\ f &= -\pi b \sin(\omega t) - b, \quad (2n+1)\pi/\omega<t<(2n+2)\pi/\omega, \qquad (6.3) \\ n &= 0,1,2,3 \ldots\ldots\ldots\ldots\ldots\ldots \end{aligned}$$

where b is a constant. This equation assumes a mean f of zero over a 24 hour period. Values for the average soil temperature and b were then chosen so that the simulated temperature data (with $c_v = 3.1$ MJ m^{-3} K^{-1} and $K_h = 1.1$ W m^{-1} K^{-1}) approximated the measured data, as shown in Fig. 6.4. A mean temperature of 11.7°C and a b value of 39 W m^{-2} were used to obtain the simulated data. The difference in shape between the two curves from 1600 to 2000 h is probably due to intermittent cloud cover.

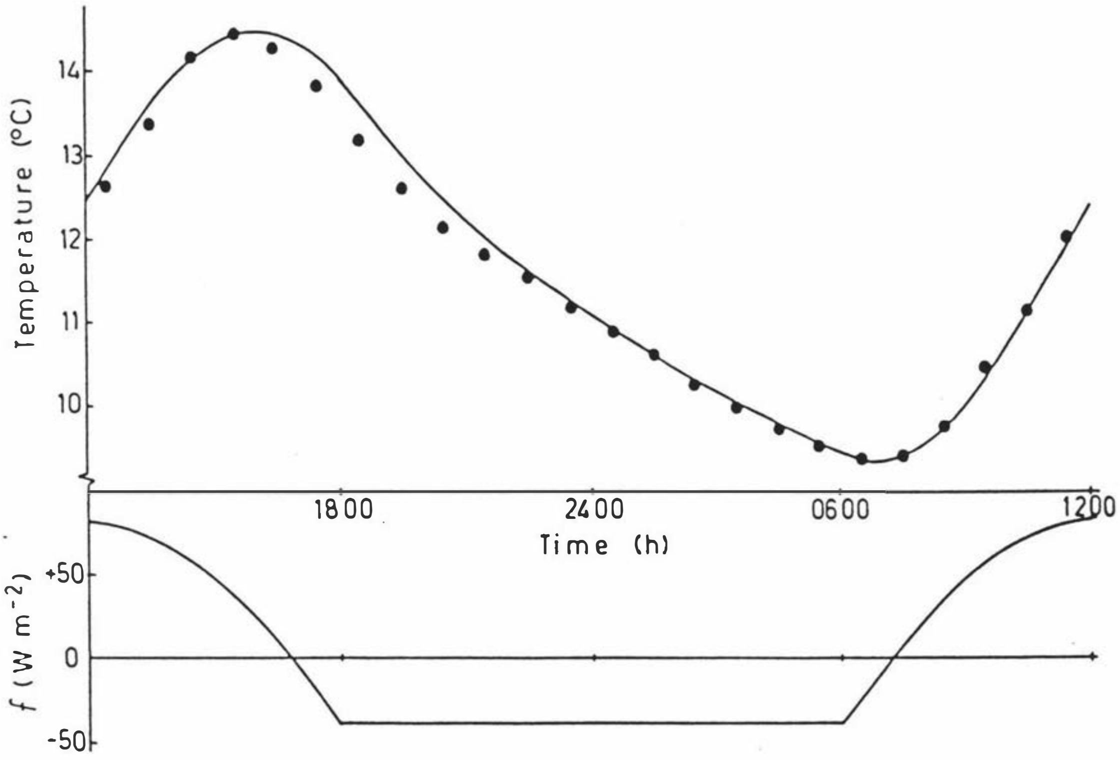


Figure 6.4 The simulated diurnal soil heat flux density (f) and soil temperature at 50 mm depth on a clear equinoctal day. Also shown are the soil temperatures measured at 50 mm depth on 9 - 10 September, 1984(●).

Equation (6.3) was then used as the boundary condition to simulate the diurnal temperature oscillations at various depths in drained soil (c_v = 3.1 MJ m^{-3} K^{-1}, K_h = 1.1 W m^{-1} K^{-1}) and undrained soil (c_v = 3.3 MJ m^{-3} K^{-1}, K_h = 1.2 W m^{-1} K^{-1}). The results are shown in Fig. 6.5. The commonly observed changes in amplitude and phase with depth are shown, as is the trend towards a more sinusoidal shape. Drainage is predicted to increase the maximum and decrease the minimum temperature at each depth, although at 50 mm depth the difference is only 0.2°C. Differences of this magnitude were found between duplicate thermistors at this depth in our experiment, so again the predicted effect of drainage is insignificant.

Finally, the following calculation is instructive. If mole drainage changes c_v in the top 450 mm of soil from 3.3 to 3.1 MJ m^{-3} K^{-1}, and the summer topsoil temperature is 11°C warmer than the winter temperature, then the extra heat required to warm the undrained soil compared to the drained soil is 1 MJ m^{-2}. This corresponds to the energy required for 0.4 mm of evapotranspiration, which can occur in an hour on a mild spring day, and is an insignificant fraction of the net radiation and soil heat flux during spring.

In summary, it can be said that if the surface is bare, it is predicted that drained soils will warm up slightly more quickly in spring than undrained soils. However, the expected differences in soil temperature between drained and undrained plots with a full cover of pasture will be very small and hard to detect. It must be concluded therefore, that the well entrenched notion, that by draining a soil under pasture, spring-time temperatures are increased, is a fallacy and is not the reason for the enhanced regrowth rates observed on the drained plots.

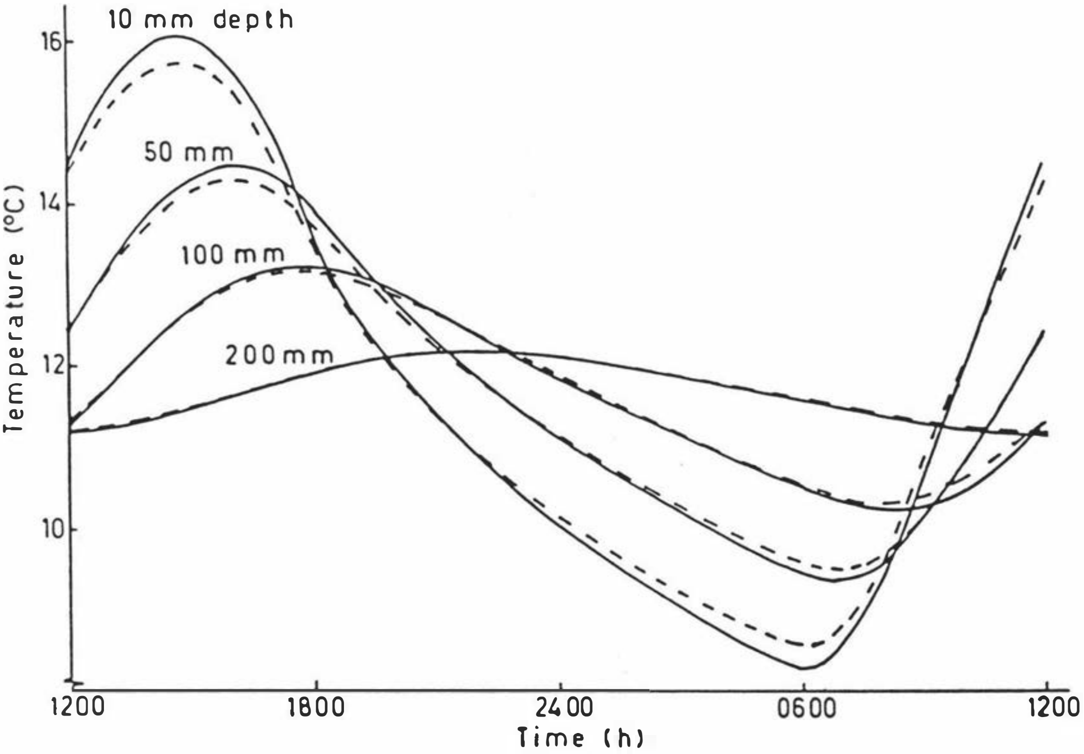


Figure 6.5 Simulated diurnal soil temperatures at four depths in drained (——) and undrained (– – –) soil .

6.3.2 Effect of drainage on soil aeration

6.3.2.1 Soil aeration in an undrained soil

Though no measurements were made of soil aeration in this study, as a claimed benefit of drainage it warrants some discussion. Evidence in the literature concerning the effect of soil aeration on pasture growth is often vague and there have been few field investigations into the relationship between watertable levels, soil aeration and pasture growth.

When considering the effects of flooding, a distinction should be made between the short-term effects of low aeration and the effects of long-term waterlogging. In the first case, there is a change in environment which can temporarily impair metabolic activity and the development of the root system, whereas in the second case, the effect of prolonged O_2 deficiency is the main injurious factor (Wesseling, 1974).

If a fluctuating watertable causes waterlogging of a temporary nature in the surface soil then aerobic microbial processes might not be greatly impeded, because it has been observed that anaerobic microbial processes do not commence until the partial pressure of oxygen falls to very low values (Grable, 1966; Greenwood, 1971, 1975; Ponnamperuma, 1972). Greenwood (1975) calculates that it is unlikely that oxygen-free regions of soil will occur unless there are regions which are separated from the continuous gas phase by more than 9 mm of water-saturated soil. Also, the first pores to drain in a soil that has been completely saturated with water usually are continuous with the surface, and so would be expected to have an oxygen partial pressure similar to that in the atmosphere (Greenwood, 1975).

Even in undrained soil it is unlikely that the surface soil would remain anaerobic for prolonged periods, as it will be shown in Section 7.3 that three days after the cessation of flooding and ponding the watertable will often be at least 100 mm below the pugged soil surface.

6.3.2.2 Direct effects of soil aeration on pasture growth

If the watertable level frequently rises and declines then damage done during temporary anaerobic conditions will depend on plant species, growing stage and temperature, as well as the duration of waterlogging. While some crop species may be very sensitive to anaerobic conditions (Grable, 1967; Trafford, 1975; Feddes and Van Wijk, 1976), the pasture species perennial ryegrass and white clover are relatively tolerant of anaerobic conditions. Gradwell (1967) found that perennial ryegrass grew at optimum rates at levels of soil oxygen that would severely restrict the growth of crop plants. He found that ",,, only at very low rates of oxygen supply was the growth of the ryegrass substantially reduced". Van de Goor (1972), Cannell (1979) and Wesseling (1974) also state that grasses can withstand continuous flooding for weeks when the soil temperature is low. For white clover, Gradwell (1969) found a depression of shoot growth attributable to oxygen deficiency only occurred when the flux of oxygen was less than 1×10^{-7} $g\ cm^{-2} min^{-1}$, a value similar to the flux of oxygen required for optimum growth of ryegrass and lower than the flux required for crop plants.

It is of some interest to note that Gradwell's work revealed that when the oxygen flux was very low and there was a substantial reduction in the shoot growth of white clover, ryegrass shoots continued to grow, although root activity was retarded. It appears that white clover is more susceptible to damage than ryegrass when the soil lacks adequate oxygen.

6.3.2.3 Indirect effects of soil aeration on pasture growth

Soil aeration has an indirect effect on plant growth, as aeration is one of the properties that determine the rate at which organic matter decomposes and nutrients are released for plant uptake. Soil aeration often controls the equilibrium between the different forms of plant nutrient, such as NH_4^+ and NO_3^-, as it dictates whether the dominant processes are oxidative or reductive. The plant nutrient element N is perhaps the most sensitive to aeration conditions (Wesseling, 1974). During waterlogging, decomposition of organic matter is slowed, while part of the available N is immobilized (Broadbent and Nakashima, 1970). Also, important losses can result from denitrification, when microorganisms reduce NO_3^- to nitrite, nitrogen oxide or nitrogen gas (Foth, 1978).

As nitrates may be quickly lost by leaching, and because mineralisation is decelerated at high moisture contents, it is possible that N deficiency is at least partially responsible for the slow recovery of some crops after flooding (Grable, 1966). Hoogerkamp and Woldring (1967) state that the watertable level has some effect on the available N present in soil. Van Hoorn (1958) found that the effect of increased watertable depth on crop yields was similar to that caused by N fertilizer, and the depression in yield caused by a shallow watertable could be compensated for by increasing the nitrogen dressing.

No differences in the quantity of plant available N to a depth of 75 mm were measured between drainage treatments, as discussed in Section 5.3.3.2. Presumably aeration at the soil surface on the undrained plots was sufficient to ensure a mineralisation rate comparable to that on the drained plots. Also, apparently watertable levels in the top 75 mm of the undrained profile were not creating an environment in which greater quantities of NO_3^- were being reduced than was the case for the drained plots.

It might be argued,that for a soil with a fluctuating watertable, a difference between drained and undrained plots in the level of plant available N in the top 75 mm of the profile would not be expected. Only deeper down in the undrained plots, in more permanently waterlogged zones, would available N levels be lower than those on drained plots. However, it must be remembered that approximately 70% of the root activity of pasture is confined to the top 80 mm of both the drained and undrained profile on the experimental site, as illustrated in Fig. 5.5 and 5.6. Therefore, pasture roots may not be able to thoroughly capitalize on any benefits drainage may offer in increasing N levels deeper within the profile during this period.

In conclusion,it may be said that while it is not possible to dismiss entirely the effects of poor soil aeration on the performance of poorly drained pasture land, it is unlikely that this is the primary cause of the impaired growth rates measured on the undrained plots. Poor soil aeration may have some bearing on pasture growth, but it is only likely to be a factor of any importance after grazing and severe pugging, smearing, and structural damage to the soil surface has occurred. Soil aeration is therefore considered to be, at most, a secondary factor and not primarily responsible for the poor growth rates observed on the undrained plots.

6.4 Conclusions

The following conclusions may be drawn:

i) Contrary to the categorical claims in the literature that drainage increases soil temperatures in spring, soil temperatures measured on waterlogged soil were the same as those measured on drained soil.

ii) If drainage under pasture had no significant effect on soil temperature, then increased temperatures could not have been responsible for the observed growth differences between drained and undrained plots.

iii) A simple mathematical analysis confirmed that the lowering of the soil heat capacity by drainage would not be expected to affect significantly soil temperature under pasture.

CHAPTER 7

CHAPTER 7

MODELLING THE EFFECT OF MOLE DRAINAGE ON WATERTABLE LEVELS AND THE NUMBER OF UNSAFE GRAZING DAYS

7.1 Introduction

It has been shown in previous chapters that grazing on an unsafe day has a severe and adverse effect upon the pasture sward. This long lasting effect was attributed to the interaction between the grazing animal and the wet surface soil. When the water content of the surface soil is high, the bearing strength is low so that grazing causes damage, both to the pasture cover and to soil structure. The obvious question to arise is; at what surface soil water content will grazing cease to be safe? As the water content of the surface soil is usually related to the level of the watertable, we already have established a criterion for unsafe grazing; a watertable level shallower than 200 mm from the soil surface.

Having defined unsafe grazing, it would be useful to determine how many unsafe grazing days a farmer might expect in a year. From this he might gauge whether or not mole drainage was a worthwhile financial investment. The problem, however, lies in gathering enough watertable data on which to base a prediction of the effect of mole drainage on watertable levels and safe grazing for different years. It is unlikely that during the course of a short investigation, the researcher will encounter a dry year, an average year and a wet year, as the results of this project illustrate. Some of the problems associated with drainage research, namely the time and expense it requires (Trafford, 1975), can be circumvented by developing models to predict the effect of mole drainage on watertable levels.

Hillel (1977) defines a model as a simplified, and hence more readily definable and easier managed, version of reality. The real world, or even a small part of it, is altogether too complex for thorough comprehension or to define in detail. In dealing with any problem it is easier to imagine the system to be simpler than it really is, by considering only the most important aspects. Though this is the great strength of modelling, in that it makes an insurmountable problem manageable, it is also its weakness in that it deliberately ignores other less important aspects of the system.

When a model begins to depart markedly from the facts it becomes misleading and must be modified or replaced (Hillel, 1977). Having defined the 'primary' effects, the next most important aspects or secondary effects are included into the model and this sequence of improvement and refinement carried on until the model is sufficiently accurate in its forecast. As Hillel (1977) states "our developing knowledge of any complex system is achieved by successive approximations".

Models are best expressed in the precise and objective language of mathematics. An equation which describes how the system behaves must be formulated from the experimental data. The equation can then be used to anticipate how the system would behave under changed circumstances, and a check made against these predictions.

In recent years, high level simulation languages (such as CSMP) have been developed which make the task of solving mathematical models using computers relatively simple. As a digital computer makes one computation at a time and is incapable of operating continuously, a computer can solve differential equations describing dynamic systems by imitating continuous processes using small but finite differences rather than derivatives (Hillel, 1977; de Wit and van Keulen, 1975).

No model describing realistically, yet simply, the influence of pipe-mole drainage on the watertable appears to exist. Unhanand and Kadir (1975) describe analytically the watertable decline following flooding of uniform soil with a pipe-mole system but go no further than that. Armstrong et al. (1980) used an equation developed by van Schilfgaarde (1965) to model watertable responses to climatic inputs, and to demonstrate the clear superiority of a pipe-mole drainage system over a system of pipes alone at 20 m spacing. However, their model assumes a uniform hydraulic conductivity and drainable porosity, and for this and other reasons is overly simplistic. A model proposed by Broughton and Foroud (1978) realistically describes the soil water balance, but describes even more simplistically and empirically than Armstrong et al. (1980) the storage and flow of soil water. There is therefore, a need for a model which can accurately predict watertable levels in drained and undrained soils.

In this chapter, a simple model is described for predicting watertable levels in both undrained and pipe-mole drained Tokomaru silt loam. The watertable model is then expanded to predict the number of unsafe grazing days in a year. Comparing the effect of mole drainage on the number of unsafe grazing days for years with different winter-spring rainfall is an important step towards quantifying the benefits of mole drainage.

7.2 Overview of Soil Water Statics and Dynamics

Soil water has a total potential energy (Φ), as a result of the net sum of all of the forces acting upon it within the soil. There are three component potentials that contribute to this total; the pressure potential (P), the gravitational potential (Z) and the osmotic potential (Π), and they are related as follows:

$$\Phi = Z + P + \Pi . \tag{7.1}$$

Wherever the potential energy of soil water differs from one point to another, then there will be flow as water moves from a position of higher energy to that of lower energy.

The influence of Π on such movement is confined to cases where solutes are present in the soil-water system and a phase change occurs. For water movement in most New Zealand soils, Π is a factor which can be neglected. Thus, we need consider only $P + Z$, a sum often called the hydraulic potential (ϕ). The pressure potential (P) can be either positive or negative. It is positive beneath the watertable due to hydrostatic pressure, and negative above the watertable due to the attractive forces between water and the solid particles of the soil matrix induced by surface tension and adsorption.

In soil water movement studies it has become common practice to express potentials as energy per unit weight of water (or head units), giving dimensions of length. The gravitational potential (Z) is then equal to the negative value of the depth z (mm) relative to some reference level, the soil surface often being a suitable reference. Using these units we can write

$$\phi = P - z \tag{7.2}$$

where z is the depth below the soil surface.

Horizontal water movement through a saturated isotropic soil is described by Darcy's equation which expresses the flow rate Q ($mm^3\ d^{-1}$) as a function of the saturated hydraulic conductivity of the soil K ($mm\ d^{-1}$), the hydraulic potential (ϕ) and the cross sectional area A (mm^2) through which flow occurs.

The equation is

$$Q = -KA\,\nabla\phi . \tag{7.3}$$

For horizontal, one dimensional flow in the x direction, this equation simplifies to

$$Q = -KA\,dP/dx . \tag{7.4}$$

Darcy's equation may also be used to describe unsaturated flow. For unsaturated flow in the vertical direction the equation is

$$Q = -kA\,d\phi/dz \tag{7.5}$$

where k is the unsaturated hydraulic conductivity (mm d^{-1}) and is a strong function of the water content and so of the matric potential of the soil.

7.3 A Model to Predict Watertable Levels in an Undrained Soil

7.3.1 The relationship between depth (z), pressure potential (P) and volumetric water content (θ)

Before water movement in a soil profile can be described, knowledge of how the pressure potential (P) varies with depth (z) and the relationship between P and θ for the particular soil is needed. To facilitate the modelling of water movement in the soil profile the following assumptions were made.

(i) Soil water above the watertable is at potential equilibrium with the watertable at all times i.e. ϕ is constant with depth in the top 450 mm of the soil profile. For justification of this assumption see Appendix D.

(ii) θ is a linear function of P and hysteresis is insignificant over the range of interest (i.e. $0 \geqslant P \geqslant -450$ mm).

(iii) There is no water movement below a level of 450 mm once the profile has rewet in late autumn or early winter. For justification of this assumption see Section 7.4.1 below.

The reason for the choice of 450 mm in the above assumptions will become apparent when the model for a drained soil is considered in Section 7.5, as 450 mm is the depth of the mole channel.

Using the published soil water retentivity data of Scotter et al. (1979a), along with assumption (ii) an expression for θ as a function of P was derived. Assumption (ii) leads to the following equation for the volumetric water content (θ) of the soil in horizons above the watertable.

$$\theta = a_i P + f_i \tag{7.6}$$

where a_i (mm^{-1}) and the porosity f_i are constants for soil layer i. Below the watertable

$$\theta = f_i. \tag{7.7}$$

Assumption (i) leads to expression (7.8) relating P to z

$$P = z - T \tag{7.8}$$

where T equals the depth from the soil surface to the watertable in mm.

7.3.2 The relationship between the equivalent depth of water in the soil profile (W) and the watertable level (T)

Using the preceding functional relationships between θ , P and T, T may be expressed as a function of W (mm), the equivalent depth of water in the soil profile. Combining equations (7.6) and (7.8) we find θ at depth z is given by

$$\begin{aligned} \theta &= a_i(z-T) + f_i \quad \text{for} \quad z < T \\ \theta &= f_i \quad\quad\quad\quad\quad \text{for} \quad z \geqslant T. \end{aligned} \tag{7.9}$$

W in the top 450 mm depth of soil is given by

$$W = \int_0^{450} \theta dz = \int_0^{T} \theta dz + \int_T^{450} \theta dz \tag{7.10}$$

where $0 \leqslant T \leqslant 450$ mm. Thus,

$$W \;=\; \int_{o}^{T}[a_i(z-T) \;+\; f_i]\,dz \;+\; \int_{T}^{450} f_i dz. \qquad (7.11)$$

Integration yields a series of quadratic equations relating W and T, of the form

$$\alpha_i T^2 \;+\; \beta_i T \;+\; (\delta_i - W) \;=\; 0 \qquad (7.12)$$

where $\alpha_i(\mathrm{mm}^{-1})$, β_i and $\delta_i(\mathrm{mm})$ are the constants applicable when T is in layer i.

Thus, given W, T may be found using

$$T \;=\; -\beta_i \;-[\beta_i^2 \;-\; 4\alpha_i\,(\delta_i - W)]^{\frac{1}{2}}/2\alpha_i. \qquad (7.13)$$

Using published soil water data for the Tokomaru silt loam, collected at a site 3 km from the Keeble farm (Scotter et al., 1979a), the top 450 mm of the soil profile was treated as four layers with the properties given in Table 7.1.

By way of an example, the values of the coefficients α_1, β_1 and δ_1 are determined below for when the watertable is in the first or top layer of the soil profile. Equation (7.11) becomes

$$W = \int_{350}^{450} (0.419)dz + \int_{250}^{350} (0.447)dz + \int_{150}^{250} (0.486)dz + \int_{o}^{T} [.00024(z-T) + 0.566]dz. \qquad (7.14)$$

Integration and rearrangement gives

$$0 \;=\; -0.00012\,T^2 \;+\; (220.1 - W), \qquad (7.15)$$

and so values of $-0.00012\ \mathrm{mm}^{-1}$, 0, and 220.1 mm for α_1, β_1 and δ_1, respectively. Values of α_i, β_i and δ_i are shown in Table 7.2, along with the range of W for which they apply.

A plot of equation (7.13) i.e. the equivalent water depth in the top 450 mm of soil (W) against the depth of the watertable (T) appears in Fig. 7.1. The most striking feature of the graph is the sensitivity of the watertable height in the top 100 mm of the soil profile to any change in the water content. If the watertable is at the surface a change of

Table 7.1 Soil water data for the four layers of Tokomaru silt loam under consideration, along with the value of the coefficient a_i defined by equation (7.6) for each layer.

Depth interval (mm)	i	Θ at $P = -500$ mm	f_i	a_i (mm^{-1})
0-150	1	0.445	0.566	0.00024
150-250	2	0.390	0.486	0.00019
250-350	3	0.367	0.447	0.00016
350-450	4	0.392	0.419	0.00005

Table 7.2 Coefficients for use in equation (7.13) along with range of W for which they apply.

Depth interval (mm)	i	α_i (mm^{-1})	β_i	δ_i (mm)	Range of W (mm)
0-150	1	-0.00012	0	220.1	$220.1 \geqslant W \geqslant 217.4$
150-250	2	-0.000095	-0.0075	220.7	$217.4 > W \geqslant 212.9$
250-350	3	-0.00008	-0.015	221.6	$212.9 > W \geqslant 206.5$
350-450	4	-0.000025	-0.0535	222.3	$206.5 > W \geqslant 193.2$

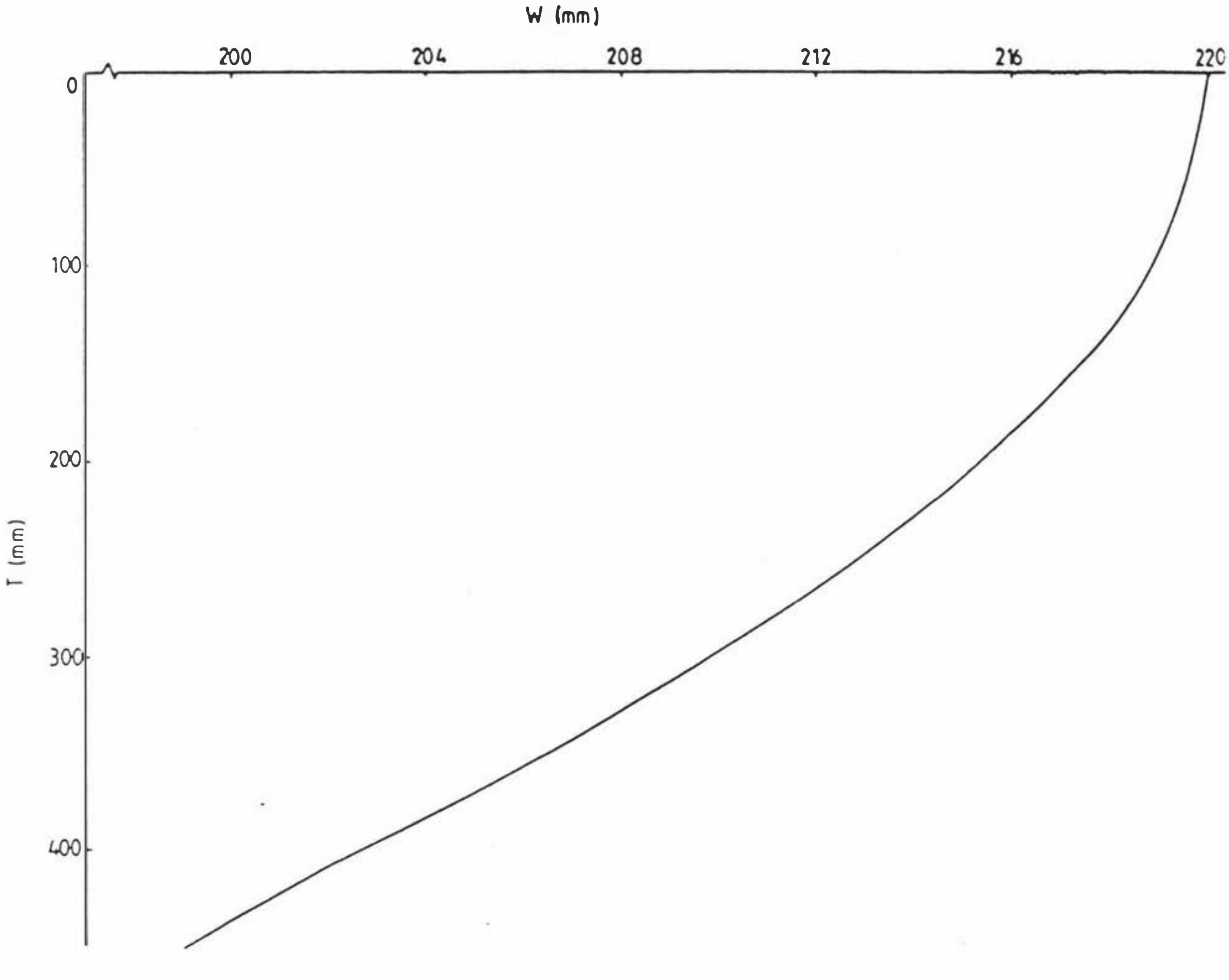


Figure 7.1 Equivalent depth of water (W) in the top 450 mm of the soil profile as a function of watertable depth (T) .

1 mm in the water content due to evapotranspiration will cause the watertable to drop 96 mm, whereas the next 1 mm of evapotranspiration will cause a drop of only 36 mm. This rapid initial decline in the watertable height away from the surface to approximately 100 mm, followed by a more gradual lowering, is in keeping with what was observed in the field after heavy rain. Conversely for rainfall; if the watertable is 100 mm below the surface then 1 mm of rainfall will bring it to the surface.

7.3.3 Evaluating the water content of the soil (W) from weather data

Having established the relationship between W and T, given W we can find T, and vice-versa. The daily change in the water stored in the profile (ΔW) of undrained soil can be calculated using the following equation (Rose, 1966).

$$\Delta W = R - E - S - U \qquad (7.16)$$

where R = rainfall (mm d^{-1})

E = evapotranspiration (mm d^{-1})

S = surface runoff (mm d^{-1})

U = deep drainage (mm d^{-1}).

Due to the very densely packed nature of the Tokomaru silt loam fragipan (Section 2.2), the impermeable subsoil restricts all or most deep drainage through to the underlying soil once the profile has wet up. Therefore, the deep drainage term (U) in equation (7.16) can be omitted (Scotter et al., 1979a). Similarly it is assumed that lateral flow can be neglected, because without subsurface drainage on the relative flat site, the watertable is nearly horizontal and lateral movement negligible.

Equation (7.16) may thus be simplified to

$$\Delta W = R - E - S. \qquad (7.17)$$

If the amount of water stored in the soil profile (W) is known on a particular day, along with the weather data (giving R and E) for all subsequent days, then ΔW and so W can be calculated for each day using equation (7.17). Once W is known for any day then the position of the watertable for that day can be calculated using equation (7.13) with the appropriate coefficients from Table 7.2.

There remains one further matter to clarify. That is what will be the magnitude of the surface runoff term (S) in equation (7.17) following heavy rainfall? Ven Te Chow (1964) suggests that anywhere between 1 and 5 mm of water can accumulate on the soil surface before runoff begins. This is called surface detention of water, as it describes the water that ponds on the surface and is unable to leave as runoff. This water must be evaporated before the watertable drops below the surface. Surface detention is most likely attributable to small localized differences in the microtopography and/or indents in the soil surface caused by the grazing animal when the watertable is high and the soil is susceptible to impact and pugging damage. Such ponding was commonly observed on the undrained plots following heavy rain. Surface runoff (S) was only assumed to occur when T was 2 mm above the mean surface level to take surface detention into account. Therefore, following surface runoff there must be 2 mm evapotranspiration before the watertable starts to drop below the soil surface. Thus, for any day

$$\text{if} \quad W > 222.1 \quad \text{then} \quad S = W - 222.1 \qquad (7.18)$$

where 222.1 mm is the sum of the equivalent depth of water in the soil profile when the watertable is at the surface (220.1 mm) plus the 2 mm of water present due to surface detention.

7.4 Running the Model for an Undrained Soil

7.4.1 1983 - an average year

To initialize the model, either the watertable level (T) or the water content (W) must be known. From that day on, with the aid of water balance data, a budget of W was run and consequentially watertable levels calculated. Rainfall (R) was recorded by a continuous recorder located on site, and Priestly and Taylor evapotranspiration rates (E) were calculated as described by Scotter et al., (1979b) from data collected at Grasslands Division, DSIR about 5 km from the experimental site.

The model was started on the 19 July, because the watertable had been at the surface twice previously, and it was considered most likely that the soil profile had rewet thoroughly following the moisture deficit incurred over the summer months.

A comparison of the computed values of the watertable height with those measured on undrained Plots 5 and 7 is made in Fig. 7.2a. The watertable depths measured in the observation wells on Plot 3 have been omitted from the measured data presented in Fig. 7.2. As discussed in Chapters 3 and 4, much of Plot 3 behaved in a different manner to the rest of the undrained plots. It was proposed that the likely reason for this was a difference in topography as some of Plot 3 was elevated above the rest of the research area. As a consequence, the watertable levels measured in some of the observation wells on Plot 3 were often lower than those measured on other undrained plots. This implies that in fact the horizontal gradient on the watertable on much of Plot 3 was not zero as assumed in the model and so the watertable was dropping more rapidly than would be expected under a flat surface.

Good agreement is observed between measured and modelled values in Fig. 7.2a, with the model predicting 67 days for which the watertable

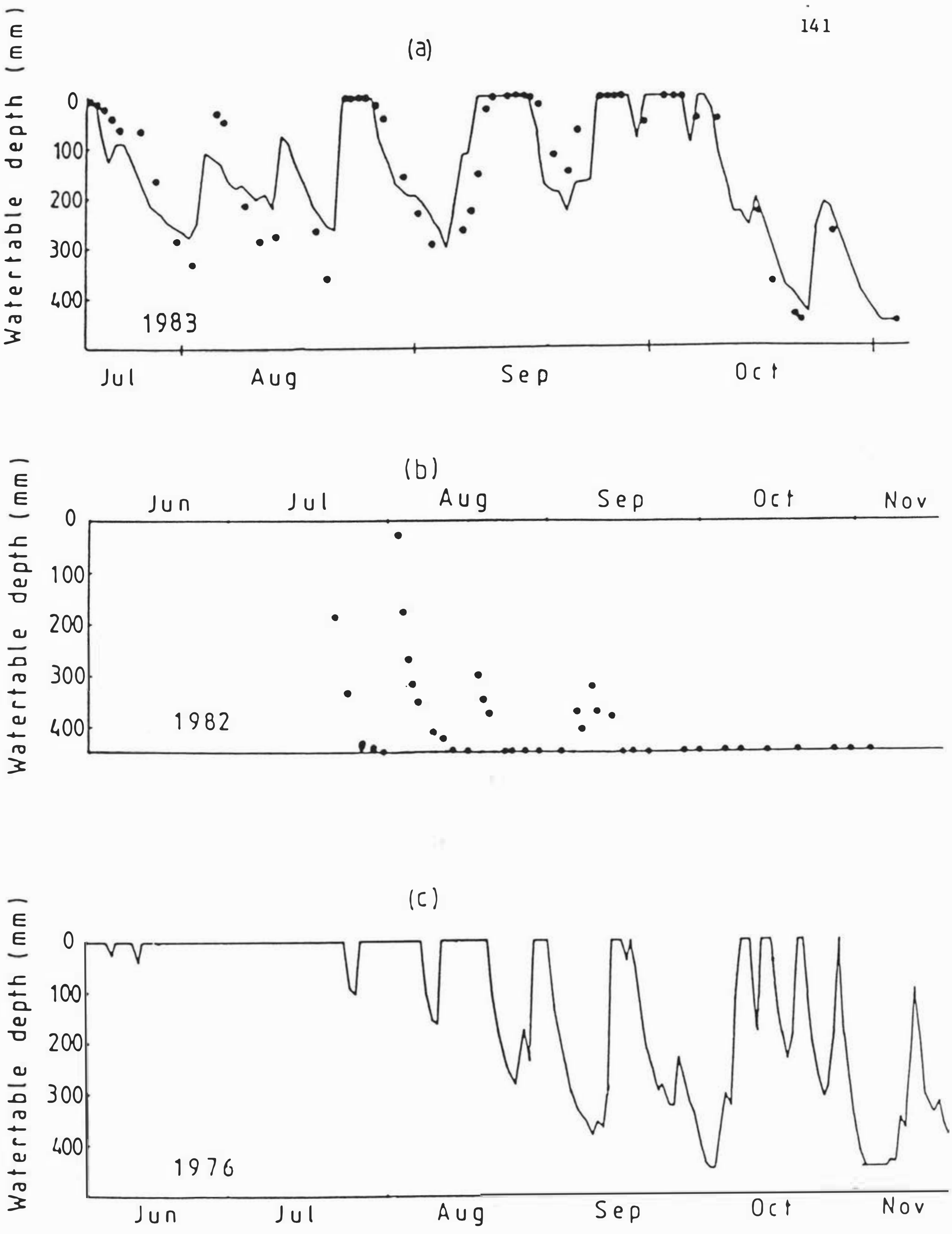


Figure 7.2 A comparison of simulated (——) and measured (●) watertable levels in an undrained soil for (a) 1983 and (b) 1982. Also shown (c) is the simulated watertable level in undrained soil in 1976. If the watertable was deeper than 450 mm it was assigned a value of 450 mm .

was shallower than the minimum level for safe grazing (200 mm) compared with 64 measured days. The modelled and observed values do not coincide as well when the watertable is close to the soil surface as they do when it is deeper in the profile. This is because, as discussed above, the model is very sensitive in this region (the top 100 mm). Thus, any inaccuracy in the value of W, say from a small error in the rainfall measurements, will cause large discrepencies in T.

One important conclusion that can be drawn from this graph is that it vindicates assumption (iii) above, that the deep drainage component (U) of the expression for water movement within the profile (equation 7.16) was indeed negligible. This serves to highlight the internal drainage problem the Tokomaru silt loam has, as there is no escape for excess water down through the profile, causing a perched watertable for many days during winter and spring. This means that excess water can only be removed from the undrained profile as either evapotranspiration or surface runoff.

7.4.2 1982 - a dry year

To determine whether the model could accurately predict watertable levels for an unusually dry winter-spring, a comparison of predicted watertable heights was made against those measured during 1982. The results are shown in Fig.7.2b. Once again, the model proved to be quite accurate at predicting the number of days the watertable was shallower than a level of 200 mm from the soil surface, with a predicted value of 0 days compared with 3 measured days.

The model predicts that the watertable would not have risen above a level of 450 mm. The reason for this is that the small volume of rainfall that fell over the autumn-early winter period of 1982 was insufficient to thoroughly rewet the soil profile and bring it back to 'field capacity'. If the end of October 1981 is taken as the last time the soil was at field capacity, a crude water balance can be calculated by subtracting potential evapotranspiration from rainfall. At the end of the relatively dry 1981/1982 summer, soil water storage relative to 'field capacity' had fallen to -200 mm. Scotter et al. (1979a) found that up to 240 mm could be extracted by pasture from Tokomaru silt loam, so a deficit of this size is feasible in this soil. For the following autumn-winter months, there was only 170 mm more rainfall than evapotranspiration, clearly not enough to fully recharge the whole profile. So if field capacity is not reached, the model predicts the watertable will not rise above the mole depth of 450 mm from the soil surface.

It is probable, that where disagreement in Fig. 7.2b is most pronounced (for example on the 21 July, and 3 - 6 August) water was being temporarily 'held up' in the soil profile. The soil had not properly rewet, and incoming water took some time to distribute itself throughout the profile, causing a temporary watertable to occur.

7.4.3 1976 - a wet year

For the two years discussed to date, 1983 and 1982, it is possible to check the values the model predicted with those measured on the research area. Having to some extent established the validity of the model, it may now be used to predict the watertable levels for other years when no measurements were made. As a comparison with a dry year and an average year, the model was used to predict watertable levels for the wet year 1976. During the months of June through to October 1976, 687 mm of rain fell, making it one of the wettest winters on record with the winter rainfall falling in the 95-100 percentile range.

A plot of the predicted watertable heights for the winter and spring of 1976 appears in Fig. 7.2c. As there were no measured values of the watertable level with which to initialize the model, the water balance described by Scotter et al. (1979b) was used, from which it was calculated that by 2 June the profile was thoroughly rewet.

The watertable in the Tokomaru silt loam is close to the surface for a considerable number of days if the volume of rain falling over the winter and spring months is large. The predicted number of days in 1976 the watertable was above the level of 200 mm from the surface was 113, compared with 67 days for the average year 1983.

7.5 A Model to Predict Watertable Levels in a Pipe-Mole Drained Soil

7.5.1 Lateral movement of soil water due to drainage

In Section 7.3.3, for the undrained soil, we ignored sideways movement because the watertable gradient was considered too small to induce any appreciable sideways movement. But in drained soil, due to the action of the mole drain, this component of lateral movement will be an important term in equation (7.16) as the watertable usually has a gradient towards the mole, along which water can flow.

To evaluate horizontal water flow to the mole drains we assume that such movement will occur only in saturated soil and that the saturated hydraulic conductivity (K) is constant with time. In fact, as was pointed out in Section 3.3.2, some flow was observed in the drains in early winter before the soil became saturated, but this was due primarily, to the preferential flow of some of the free water present in the profile down cracks and channels formed during summer drying rather than movement through the bulk of the soil.

The Dupit-Forchheimer (DF) assumptions may be applied to water movement through the soil to the moles. These assumptions are in effect that saturated flow above the watertable is horizontal and that the pressure head gradient inducing this flow is equal to the slope of the watertable and is invariant with depth (Kirkham and Powers, 1972). Applying the DF assumptions to Darcy's equation for horizontal flow (7.4) gives for flow to the moles

$$Q = -KA\, dT/dx. \tag{7.19}$$

Consider the soil adjacent to length y of mole drain with a height h through which flow occurs. Then

$$h = z_m - T \tag{7.20}$$

where z_m is the depth to the mole drain. Substituting equation (7.20) into equation (7.19) yields the following expression for flow towards the mole

$$Q = K\, y\, (z_m - T)\, dT/dx. \tag{7.21}$$

7.5.2 Effect of lateral flow on the watertable level

To enable the determination of the volume of water flowing from the soil to the mole, the soil profile was considered as a series of compartments as depicted in Fig. 7.3.

The law of conservation of mass gives the following equation for the change in the equivalent depth of water in compartment c during time t,

$$\Delta W_c = \{[(Q_{c-1} - Q_c) + (R_{c-1} - R_c)]/\, y\Delta x + D\}\, \Delta t \tag{7.22}$$

where Q_c, R_c Q_{c-1}, R_{c-1} and D are as illustrated and defined in Fig. 7.3. In the limit, as the values of W_c, Δt and Δx become very small, equation (7.22) reduces to

$$\partial W_c/\partial t = (\partial Q_c/\partial x + \partial R_c/\partial x)/y + D. \tag{7.23}$$

R_c is taken as zero unless the watertable is at a level 2 mm above the soil surface, in which case $\partial W_c/\partial t = 0$, and so

$$\partial R_c/\partial x = -\partial Q_c/\partial x - yD. \tag{7.24}$$

The value of Q_c is given by equation (7.21).

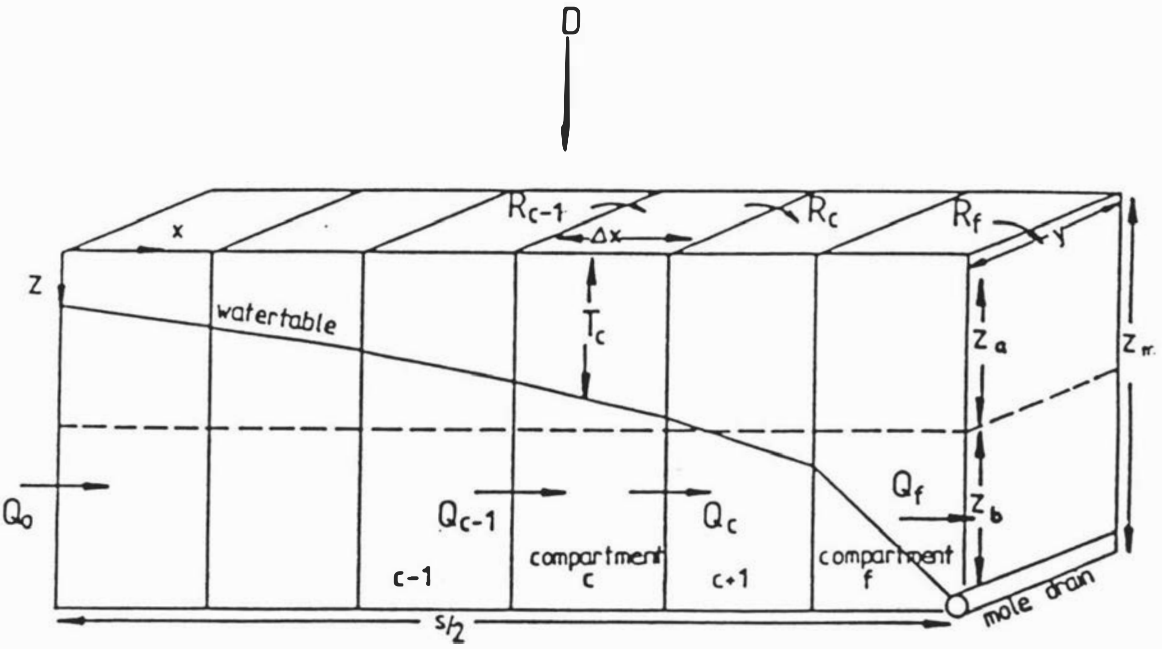


Figure 7.3 A cross-sectional view of the soil as it was imagined to be sectioned into a number (f) of compartments including compartments c-1, c and c+ 1. Q_c (mm^3 d^{-1}) is the rate at which water flows out of compartment c, Q_{c-1} is the rate at which water flows into compartment c and Q_o is the rate at which water flows across the watershed (i.e. the mid-point between the moles with a spacing s (mm)) which is equal to zero. Q_f is the flow to the mole from the final compartment (f). R_{c-1} (mm^3 d^{-1}) is the rate of surface runoff onto compartment c and R_c is the rate of surface runoff off compartment c. R_f is the surface runoff from the final compartment (f). D is the daily rainfall minus evapotranspiration .

For a soil such as the Tokomaru silt loam, where the A horizon is of width z_A (mm) with hydraulic conductivity K_A (mm d^{-1}) and the B horizon of width z_B (mm) with a hydraulic conductivity value of K_B (mm d^{-1}), the mean saturated hydraulic conductivity (K) in the x direction for compartment c is given by equations (7.25) and (7.26).

$$\text{If} \quad T \geqslant z_A \quad \text{then} \quad K = K_B. \tag{7.25}$$

$$\text{If} \quad T < z_A \quad \text{then} \quad K = z_B K_B + (z_A - T)K_A \,/(z_m - T). \tag{7.26}$$

The drainage coefficient (I) is defined as the depth of water in millimetres a drainage system removes over a period of 24 hours. It is reported by Bowler (1980) that typical values for the drainage coefficient for pasture range between 5 and 15 mm d^{-1}. Because a 'bottle neck' formed at large flows at the only outfall for the drainage system on the research site, it was calculated that 10 mm was the maximum amount of water that the drains could conduct away in any one day i.e. $I = 10$ mm d^{-1} for the drained plots (D.R. Scotter, pers. comm.). If at any time during heavy prolonged rain, the watertable was calculated to rise to a level 2 mm above the mean soil surface level, then at that time, surface runoff from the drained plots was assumed to begin.

We must then add the following constraint to equation (7.21); that the flow from the final soil compartment f, (Q_f) to the drain cannot exceed that allowed by the drainage coefficient. The flux from the final compartment (Q_f) into the mole is given by either the appropriate finite difference form of Darcy's equation, assuming T at the mole equals z_m, i.e.

$$Q_f = K_f y(z_m - T)^2/(2\Delta x), \tag{7.27}$$

or the limiting flux determined by the drainage coefficient,

$$Q_f = I(s/2)y, \tag{7.28}$$

whichever is smaller.

The sum of Q_f over a day yields the predicted daily total flow in the mole, L (mm d^{-1}). Likewise a summation of R_f, the runoff from the soil for the whole day, corresponds to the daily total surface runoff, S. The daily change in the water content of drained soil can be calculated using equation (7.29)

$$\Delta W = R - E - S - L - U. \tag{7.29}$$

As shown in Section 7.4.1, deep drainage to underlying layers is practically non-existent in the Tokomaru silt loam, so U in equation (7.29) can be taken as zero. This gives rise to equation (7.30) for a drained soil, which is identical to equation (7.17) for undrained soil except for the inclusion of the term (L) which describes the effect of the mole drain on the water content of the soil profile.

$$\Delta W = R - E - S - L. \tag{7.30}$$

If the equivalent water depth in all compartments (W) is known at the start of a particular day, along with weather data for all subsequent days, then W for all compartments for each day can be calculated using the equations presented above. That is to say, computations are carried out to simulate the effect of mole drainage, rainfall and evapotranspiration on the water content of each compartment over a short time interval. If the water content of each compartment is known at the end of the time interval, the watertable level can also be calculated using equation (7.13) in conjunction with Table 7.2. After many such calculations the watertable level in each compartment at the end of the day is arrived at. By averaging the watertable depths in all f compartments, as calculated at the end of the day, the average watertable depth for the day is found.

7.5.3 Parameterisation of the model

Clearly the smaller the time step (Δt) and the compartment width (Δx) then the more closely the continuous nature of the partial differential equation (7.23) is approximated by the numerical analysis. Practical limitations, such as the computing time required for execution of calculations, impose a lower limit of about 0.001 d on the size of the time step used. On the Tokomaru silt loam, most mole drains are pulled so that the spacing between successive mole channels (s) is 2000 mm. This means that the distance from the mole to the watershed, midway between the moles (that is length s/2), is equal to 1000 mm. This section of soil, between the mole and the watershed, was partitioned into 6 compartments giving Δx a value of 166.7 mm.

Two different sets of published values for the hydraulic conductivity for horizontal flow in the saturated Tokomaru silt loam were considered for use in the model. Scotter et al. (1979a) found using the auger hole method that $K_A = 32$ mm d^{-1} and $K_B = 0.3$ mm d^{-1}, whilst Scotter et al. (1982) obtained a value for K_A of 372 mm d^{-1} by measuring steady-state inflitration of ponded water from two rings of different radii that had been slightly pressed into the soil surface. No K_B value is given by Scotter et al. (1982) so it was assumed that the value of K_B was an order of magnitude smaller than K_A.

The two quoted values for the permeability in the A horizon differ by an order of magnitude. It was suspected that the values given by Scotter et al. (1979a) of 37 mm d^{-1} and 0.3 mm d^{-1} were too small for two reasons. Firstly, these values were obtained on undrained Tokomaru silt loam and therefore take no account of the enhancement of permeability, particularly in the B horizon, caused by the action of the mole blade during the pulling of mole channels. The second reason was due to the inherent deficiencies in the auger hole technique in fine-textured soil. A common problem with this method is that the auger hole surface is easily smeared and consequently water movement into the auger hole is impeded, resulting in permeability values that are too low (Scotter, pers. comm.).

That the K_A and K_B values of Scotter et al. (1979a) were too small is clearly shown when they are used in the model to predict the decline in the flow rate in the mole following heavy rain. In Fig. 7.4 the values predicted by the model for the volume of flow in the drains are compared with those measured in the field. The time scale for each hydrograph has been referenced to the time when a flow of 0.5 x 10^{-4} m^3 s^{-1} occurred. The lines drawn are for flow in the drains with 0 and 1 mm d^{-1} evapotranspiration, which covers the likely range of evapotranspiration rates in winter and early spring. With these conductivity values the model predicts a sharper drop in flow than was observed. However, good agreement was found when the conductivity values K_A = 372 mm d^{-1} and K_B = 37 mm d^{-1} were inserted into the model, with the two different drainage rates generated from the model by using the different evapotranspiration rates encompassing all the measured rates. It was mainly on this basis, that a K_A value of 372 mm d^{-1} (from Scotter et al., 1982) and a K_B value of 37 mm d^{-1} were chosen for use in the model, rather than the values of Scotter et al. (1979a).

Fig. 7.4 suggests that an order of magnitude change in the values of the hydraulic conductivity of the soil has a similar impact on the flow rate in the drains as changing the rate of evapotranspiration from 0 to 1 mm d^{-1}. An implication of this is that, at the stage of the recession curve depicted in Fig. 7.4, the value of the hydraulic conductivity is not as critical to the performance of the model as might be expected. At higher flow rates the value of the hydraulic conductivity would be more important (with high conductivity values greatly enhancing the drainage process) except for the fact that flow in the mole is then often limited by the drainage coefficient. This relative insensitivity of the model to the value of the hydraulic conductivity will also be discussed in Section 8.2.

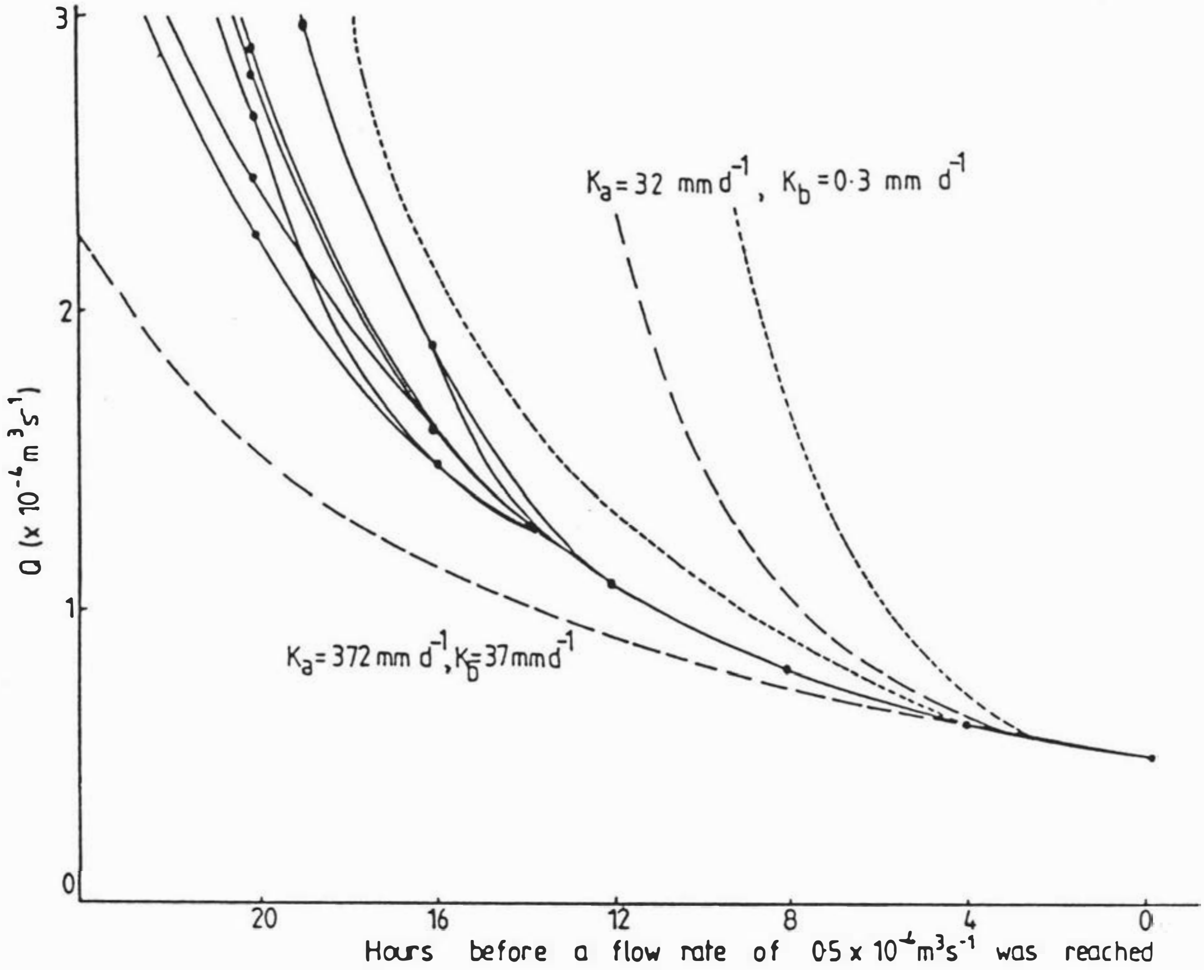


Figure 7.4 Comparisons of simulations of the decline in the rate of flow in the drainage from a 0.4 plot (Q) following rain using the hydraulic conductivity values K_A = 372 mm d^{-1} and K_B = 37 mm d^{-1} and the values of Scotter et al. (1979a) with measured rates of decline (●——●). Simulations were carried out with 0 mm d^{-1} (— —) and 1 mm d^{-1} (- - - -) evapotranspiration .

7.6 Running the Model for a Pipe-Mole Drained Soil

7.6.1 1983 - an average year

As for the undrained soil, the model was initialized by calculating the equivalent water depth (W) in the soil from the watertable level (T) measured on 19 July 1983. By inputing into the model for drained soil the same weather data (D) as for the undrained soil, a balance of W was kept and hence the watertable level over the winter-spring period of 1983 computed. A listing of the model program, along with the simulated watertable depths for the 19 July to 26 July 1983, appears in Appendix E.

A comparison of the predicted watertable heights with the levels measured on Plots 1, 4 and 8 is made in Fig. 7.5a. Agreement is quite reasonable, with the levels predicted by the model coinciding closely with the measured watertable heights. The model predicts 3 days in 1983 on which the watertable would have been less than 200 mm deep, compared with 6 days on which shallow watertables were observed on the plots.

The number of compartments (f) used in the model was found to be relatively unimportant. The greatest difference in mean watertable depths between a simulation with 10 compartments and one with 6 compartments on any day was 5 mm. The model was able to predict accurately values of mean watertable depths using as few as four compartments.

7.6.2 1982 - a dry year

As outlined in Section 7.4.2, the soil never fully rewet over the dry winter of 1982 so that 'field capacity' was not reached. The model therefore predicted that the watertable would not rise above the level of 450 mm from the soil surface. A plot of watertable levels measured in the field along with the constant 450 mm level predicted by the model is

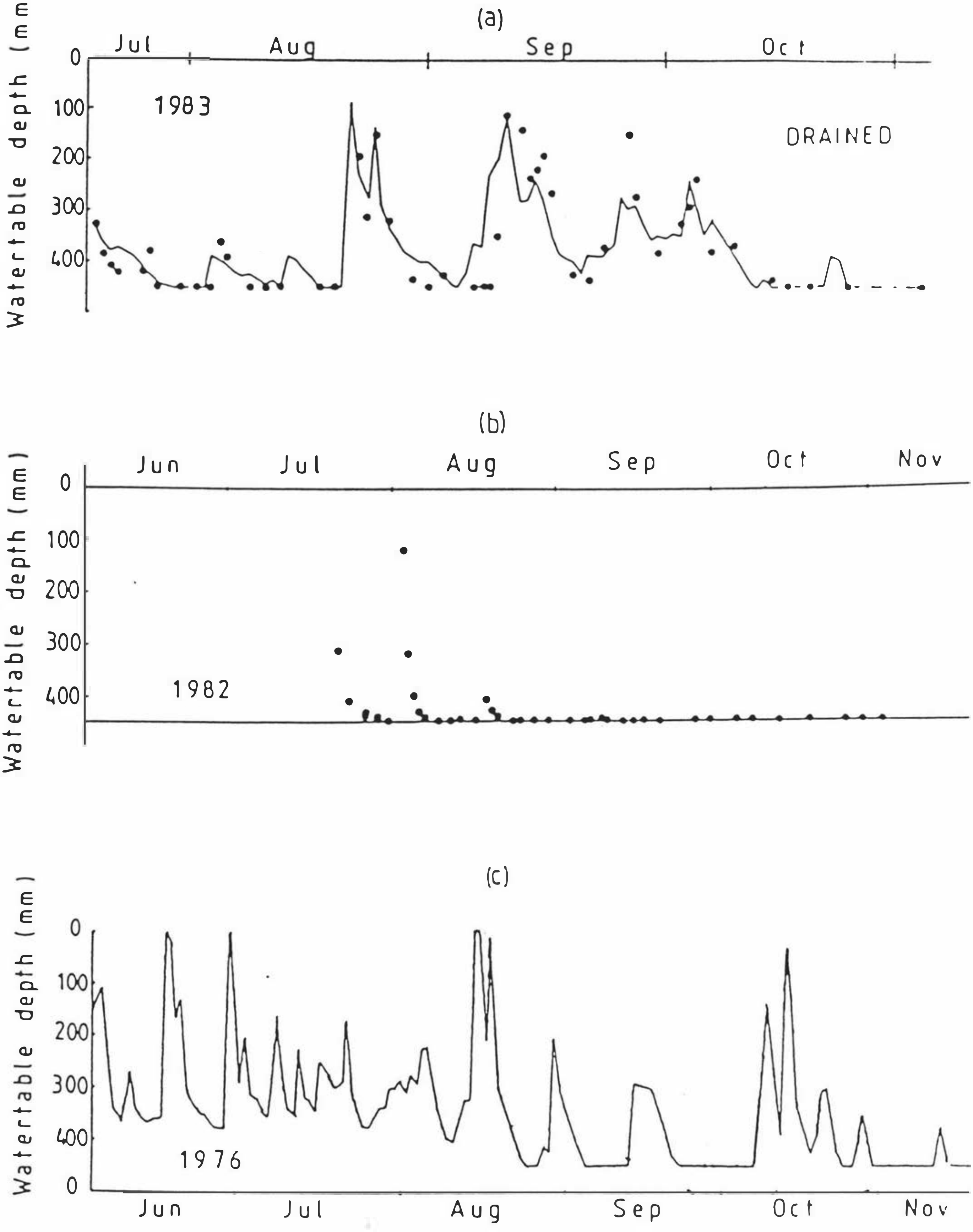


Figure 7.5 A comparison of simulated (——) and measured (●) watertable levels in a pipe-mole drained soil for (a) 1983 and (b) 1982. Also shown (c) is the simulated watertable level in a pipe-mole drained soil in 1976. If the watertable was deeper than 450 mm it was assigned a value of 450 mm .

shown in Fig. 7.5b. The model predicts 0 days for which the watertable would have been shallower than 200 mm from the surface, which agrees closely with the 1 measured day. The reasons for the poor agreement on the 22 July, 2 and 3 August were discussed in Section 7.4.2.

7.6.3 1976 - a wet year

Comparison between predicted and measured watertable levels for the years 1982 and 1983 have shown that the model is reasonably accurate in its prediction of watertable levels. Comparisons between measured data and computer simulations of surface soil gravimetric water contents are presented in Appendix F. Also in Appendix F is a comparison of measured and simulated values for mid-mole verse next to the mole watertable depths. Good agreement between these measured and simulated values further establishes the validity of the model. It was, therefore, thought reasonable to use the model to predict the watertable levels during an unusually wet year, for which no measurements of watertable levels had been made. The model was initialized by setting the watertable at an arbitrary 150 mm from the surface (compared with 0 for undrained soil) on 2 June, 1976. The weather data inputed was the same as that used for the undrained model. From Fig. 7.5c it can be seen that the number of days the model predicts the watertable would have been above the level of 200 mm from the soil surface was 20.

7.7 Comparing Simulated Watertable Levels on Drained Soil with those on Undrained Soil

The model was used to compare the differences in watertable levels for drained and undrained soils for different rainfall regimes. The model predicts large differences in the watertable levels between drained and undrained soils, clearly illustrating the benefits of drainage in an average year. In Fig. 7.6a the predicted watertable levels for the undrained soil in the winter-spring period of 1983, depicted in Fig. 7.2, are combined with the predicted values for a drained soil, as presented in Fig. 7.5.

Watertable levels predicted by the model for undrained soil (Section 7.4.2) and drained soil (Section 7.6.2) for 1982 showed that in a dry year drainage has very little effect on the level of the watertable.

The difference between the drained and undrained watertable levels is large for many days over the winter-spring period of a wet year. In Fig. 7.6b the watertable levels predicted in Section 7.4.3 by the model for the wet year 1976 for undrained soil are combined with those predicted for drained soil in Section 7.6.3. There were 113 days when the watertable would have been shallower than a level of 200 mm from the soil surface on the undrained soil as opposed to 20 such days for the drained soil. This five-fold difference in the number of safe grazing days serves to highlight both the effectiveness and importance of subsurface drainage in such wet years.

7.8 A Model to Predict the Total Number of Unsafe Grazing Days

7.8.1 The relationship between rainfall and water content of the surface soil

To date our sole criterion for determining if any given day was a safe grazing day was whether the watertable was below a level of 200 mm from the soil surface. Soil strength measurements (W. Climo, pers. comm.) and field observations indicated that it was possible for the watertable to be well below a level of 200 mm and yet the soil and pasture be susceptible to damage. This happened on days when there was rainfall.

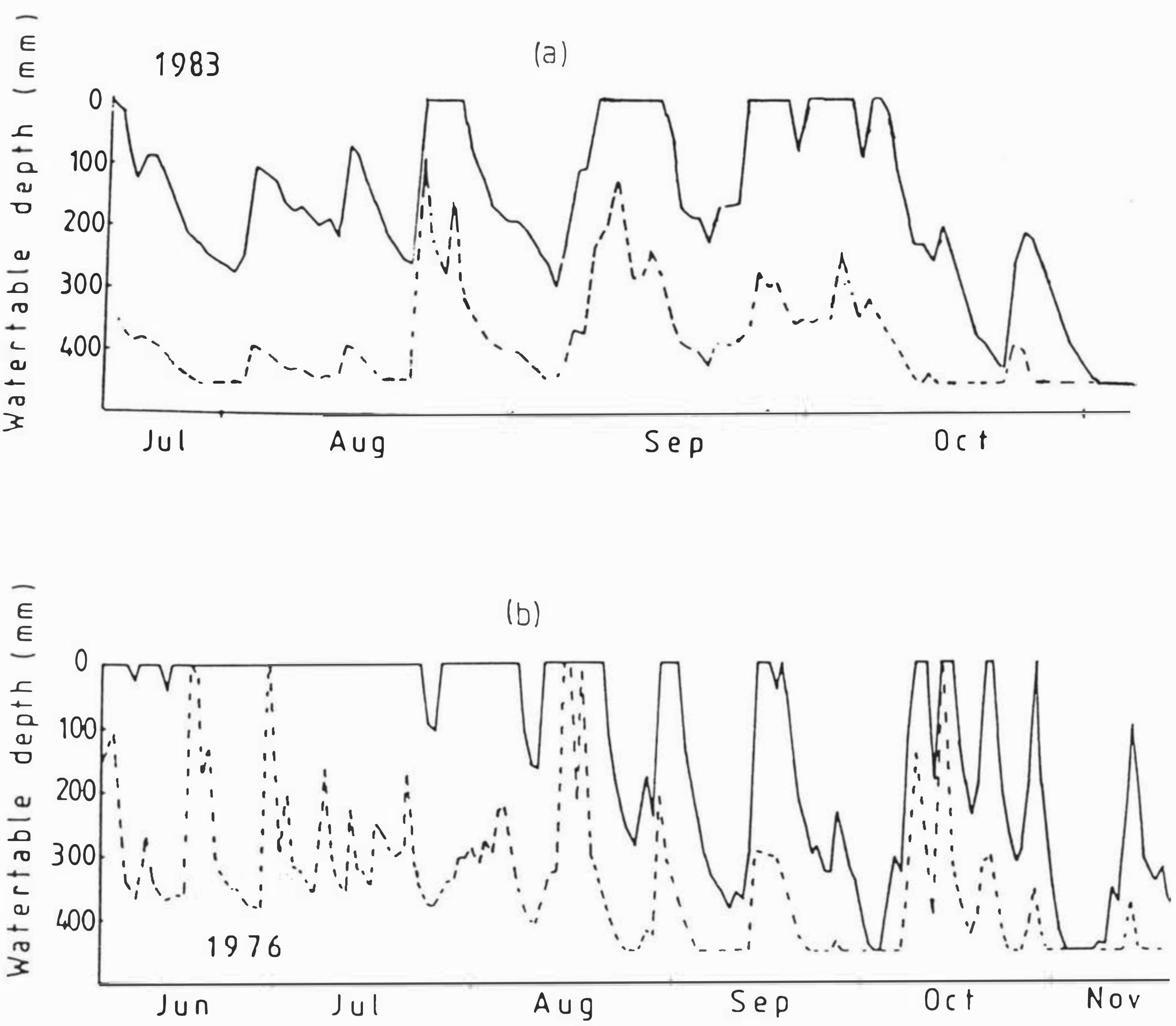


Figure 7.6 A comparison between simulated watertable levels for a pipe-mole drained (----) and undrained soil (——) for (a) 1983 and (b) 1976. If the watertable was deeper than 450 mm it was assigned a value of 450 mm .

The rain involved was not heavy enough to bring the watertable to within 200 mm of the soil surface, but was sufficient to wet the very top of the profile, lowering soil strength and making grazing unsafe. Therefore, estimates of the number of unsafe grazing days based solely on the watertable levels are inaccurate, in that they will tend to underestimate the total number of unsafe grazing days.

Thus a way of predicting unsafe grazing days due to rain wetting the surface soil needs to be added to the already discussed unsafe grazing day indicator of a watertable depth of less than 200 mm. The unsaturated hydraulic conductivity (k) of soil is very dependent on its water content, and during rainfall the surface soil must wet-up enough to conduct the excess rain through it. The daily excess (D) is the rainfall minus the evapotranspiration. Assuming steady-state gravity-induced flow in the A horizon of the soil (i.e. $d\phi/dz = -1$) then as $Q/A = D$, equation (7.5) simplifies to

$$D = k. \tag{7.31}$$

As discussed in Appendix D, a reasonable estimate of the relationship between k ($\mathrm{mm\ d^{-1}}$) and θ over the range of values of interest in the topsoil of Tokomaru silt loam is

$$k = 10^{-17} \exp(92.6\theta). \tag{7.32}$$

From equation (7.5) and Table 7.1 we estimate for the topsoil

$$\theta = 0.00019\,P + 0.486. \tag{7.33}$$

Combining equations (7.31), (7.32) and (7.33) we find

$$D = 10^{-17} \exp\left[92.6\,(0.00019\,P + 0.486)\right]. \tag{7.34}$$

Substituting a value of -200 mm for P (the equilibrium surface matric potential when the watertable is at 200 mm depth) we find D equals 10 $\mathrm{mm\ d^{-1}}$. In other words, steady rainfall of 10 $\mathrm{mm\ d^{-1}}$, in the absence of a watertable, leads to the same pressure potential and so strength in the surface soil as would equilibrium conditions and a watertable of 200 mm depth. Therefore, the total number of unsafe grazing days is determined by the number of days for which either

$$T \leqslant 200 \text{ mm} \quad \text{or} \quad D \geqslant 10 \text{ mm}. \tag{7.35}$$

7.8.2 Running the model to predict the number of unsafe grazing days

Fig. 7.7 compares the number of unsafe grazing days predicted by the model for both drained and undrained soil during the three years under consideration. In the dry year, 1982, there were only 11 days for both the drained and the undrained soil for which grazing would have been unsafe. In the year of average rainfall, 1983, the number of unsafe grazing days for the drained soil was 10 compared with 69 days for the undrained soil. This shows the importance of drainage in years of average rainfall. Although drainage had no effect on the number of safe grazing days for the dry year, drainage ensured a seven fold increase in the number of safe grazing days in the average year. For the wet year, 1976, the benefits of drainage were even more pronounced, with the undrained soil being unsafe for grazing on 119 days compared with 33 days for the drained soil.

Fig. 7.7 shows that the spring of 1983 had more days for which grazing would have been unsafe than did the spring of the wet year, 1976. If stock were allowed to graze on an unsafe day in early winter, utilisation would be poor and pugging and pasture damage would be severe, but because pasture growth rates are low at this time of the year, the effect on the years total pasture production may not be great. By the time the increased growth rates associated with spring begin, the soil and pasture may have recovered sufficiently to be producing at rates

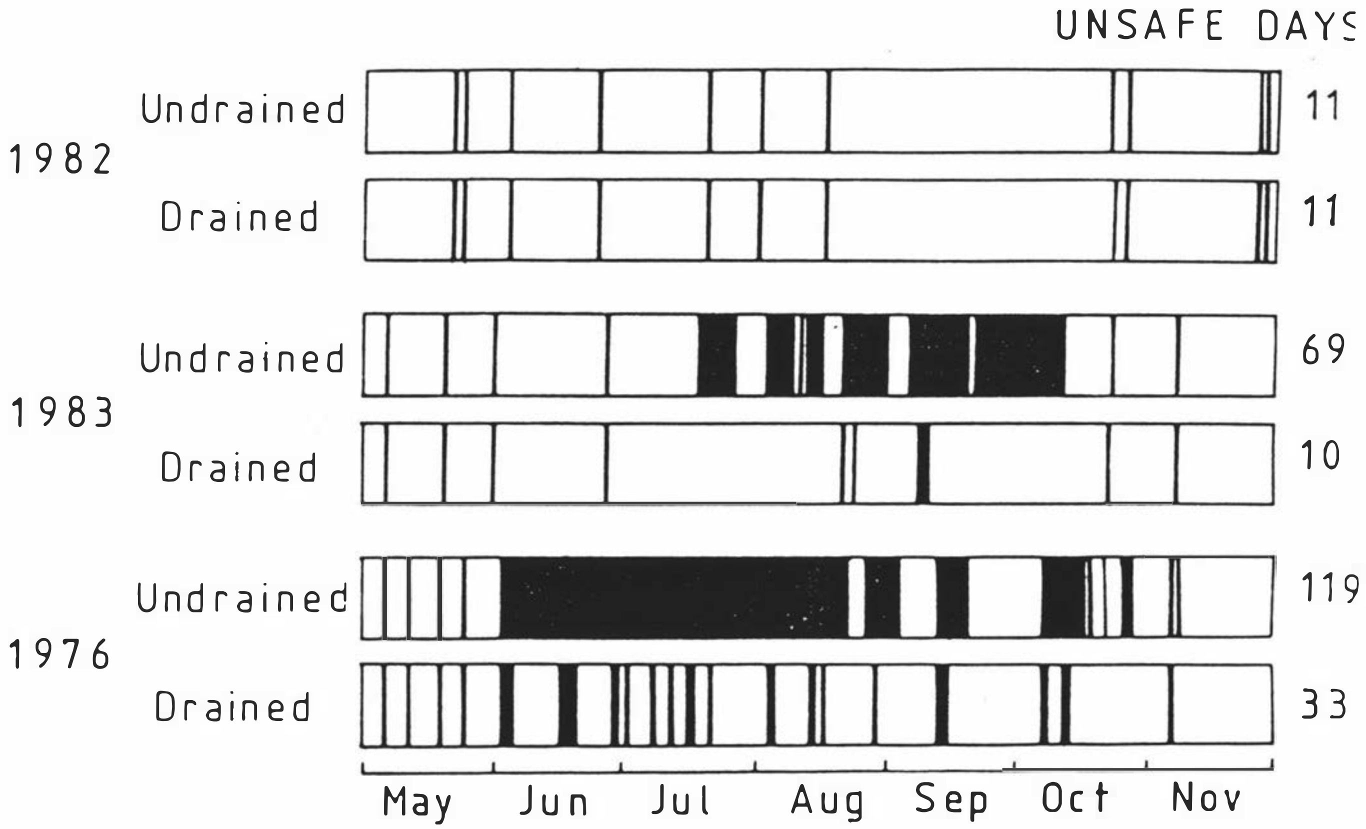


Figure 7.7 Number of unsafe grazing days on drained and undrained soil in the winter-spring period of 1982, 1983 and 1976 .

comparable with swards that were not damaged by winter grazing.

Grazing on an unsafe day in spring or late winter may have greater consequences. Utilisation will be poor and damage severe, as described for unsafe winter grazing, but because pasture growth rates are high the adverse effect on the years total production will be marked. Therefore, the susceptibility of soil and pasture to damage, if grazed when the watertable is close to the soil surface, takes on special significance in the late winter and spring period.

Poorly drained soils that cannot be grazed for as many as 69 days in an average year and up to 119 days in a wet year present a major management problem. As an aid to the easier management of grazing schedules during the winter-spring of an average or wet year, mole drainage is vital. The large reduction in the number of unsafe days in an average or wet year, brought about by the installation of mole drainage, makes drainage highly desirable for soils with internal drainage problems such as the Tokomaru silt loam.

7.9 Conclusions

The following conclusions may be drawn:

i) A simple model has been developed which shows the pronounced effect mole drainage has on the level of the watertable in an average year and a wet year.

ii) The watertable model was expanded so as to predict the total number of unsafe grazing days in a winter-spring period. Mole drainage had a pronounced effect on the number of unsafe grazing days in an average or wetter year. In a dry year, mole drainage was of little or no benefit, as the small number of unsafe grazing days was the same on both drained and undrained soil.

iii) Some idea of the magnitude of the benefits of mole drainage can be gained by predicting that in an average year mole drainage can effect a reduction from approximately 69 to 10 in the number of unsafe grazing days and in a wet year from 119 to 33.

iv) Insofar as they are able, by the use of sacrifice paddocks or standing pad, farmers should not graze sheep on Tokomaru silt loam if the watertable is less than about 200 mm from the soil surface or more than about 10 mm of rain has fallen in the last 24 hours.

CHAPTER 8

CHAPTER 8

MODELLING THE INFLUENCE OF VARIOUS PARAMETERS ON THE PERFORMANCE OF A MOLE DRAINAGE SYSTEM

8.1 Introduction

In Chapter 7 a model was developed which predicted reasonably accurately watertable levels in Tokomaru silt loam. Two obvious questions which arise are, firstly, whether or not the model can be adapted for use on other soil types with a perched watertable, and secondly, can the model be used to increase comprehension of the drainage process and/ or to improve drainage design? The answer to the first question is outside the scope of this study as it would involve obtaining soil water retentivity and conductivity data, and determining the minimum watertable depth needed for safe grazing on the soil in question. Investigations into the second question were carried out, as it was believed it was pertinent to this study and that it would be informative.

There are certain contentious issues surrounding the design of drainage systems, such as the effect of draining large areas on the flow in catchment drains or rivers. The model was used to provide information on such issues, and also to determine the effect of altering different parameters involved in the drainage process with a view to optimising drainage design. It has been established, that the desired effect of the drainage system is to lower and maintain the watertable below a depth of 200 mm. Therefore, the optimum drainage system will be the cheapest one which facilitates a rapid decline of the watertable to a level below 200 mm, thus reducing the time for which grazing is unsafe.

To lower the watertable from the soil surface to a depth of 200 mm, 4.8 mm of water must be removed from the profile (Fig. 7.1). In the following sections, the modelled rate at which 4.8 mm of water is removed from the soil for different soil properties, evapotranspiration rates, mole spacings and drainage coefficients is described and discussed.

8.2 Results and Discussion

8.2.1 Profile of watertable decline

A series of simulated profiles showing the position of the watertable between two moles, at different times, as it drops from the soil surface appear in Fig. 8.1. For the first 12 hours the watertable declines rapidly due to the permeable nature of the A horizon and the shallow soil depth from which water is being removed. After 0.45 days the average watertable depth is 200 mm (the depth for safe grazing). As the watertable enters the B horizon the permeability falls off markedly, and further decline in the watertable due to subsurface drainage is slow. It can be seen that the watertable gradient is now relatively flat and this is another reason why flow to the moles becomes small. Evapotranspiration is then the major factor causing a lowering in the watertable level, as will be discussed in Section 8.2.4. The fall in the watertable now occurs at a more regular rate as water leaves through the top of the profile at the evapotranspiration rate, which is assumed constant in this simulation.

8.2.2 Effect of varying hydraulic conductivity (K_A, K_B)

It was mentioned in Section 7.5.3, that the model is not as sensitive to a change in the values of K_A and K_B as might have been intuitively expected. Fig. 8.2 shows the effect varying the value of the hydraulic conductivity (K_A and K_B) has on the rate of decline of the watertable from

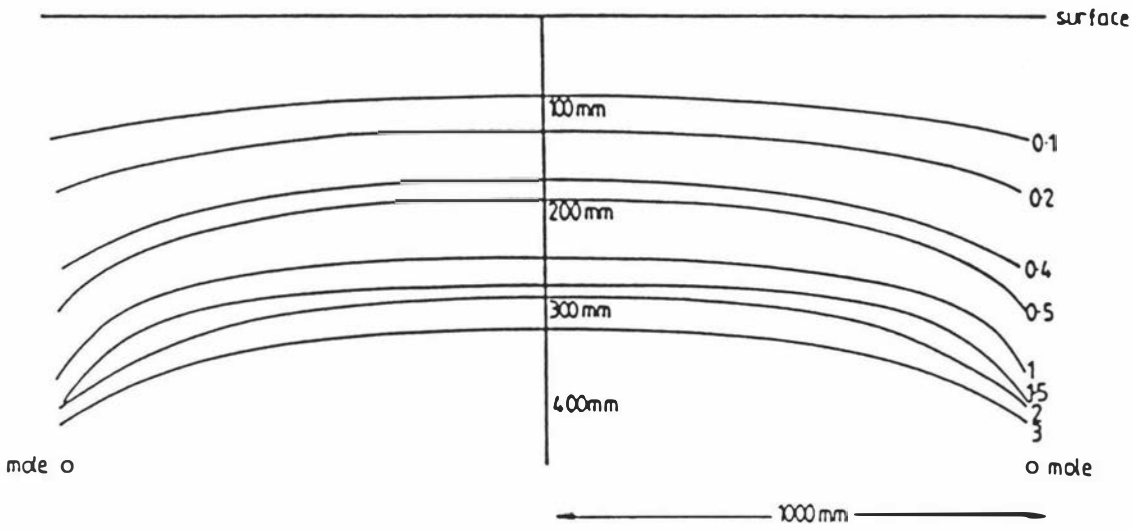


Figure 8.1 Simulation of profiles depicting the position of the watertable as it falls from the surface. A drainage coefficient of 10 mm d^{-1}, and an evapotranspiration rate of 1 mm d^{-1} have been assumed. The numbers on the curves are times in days .

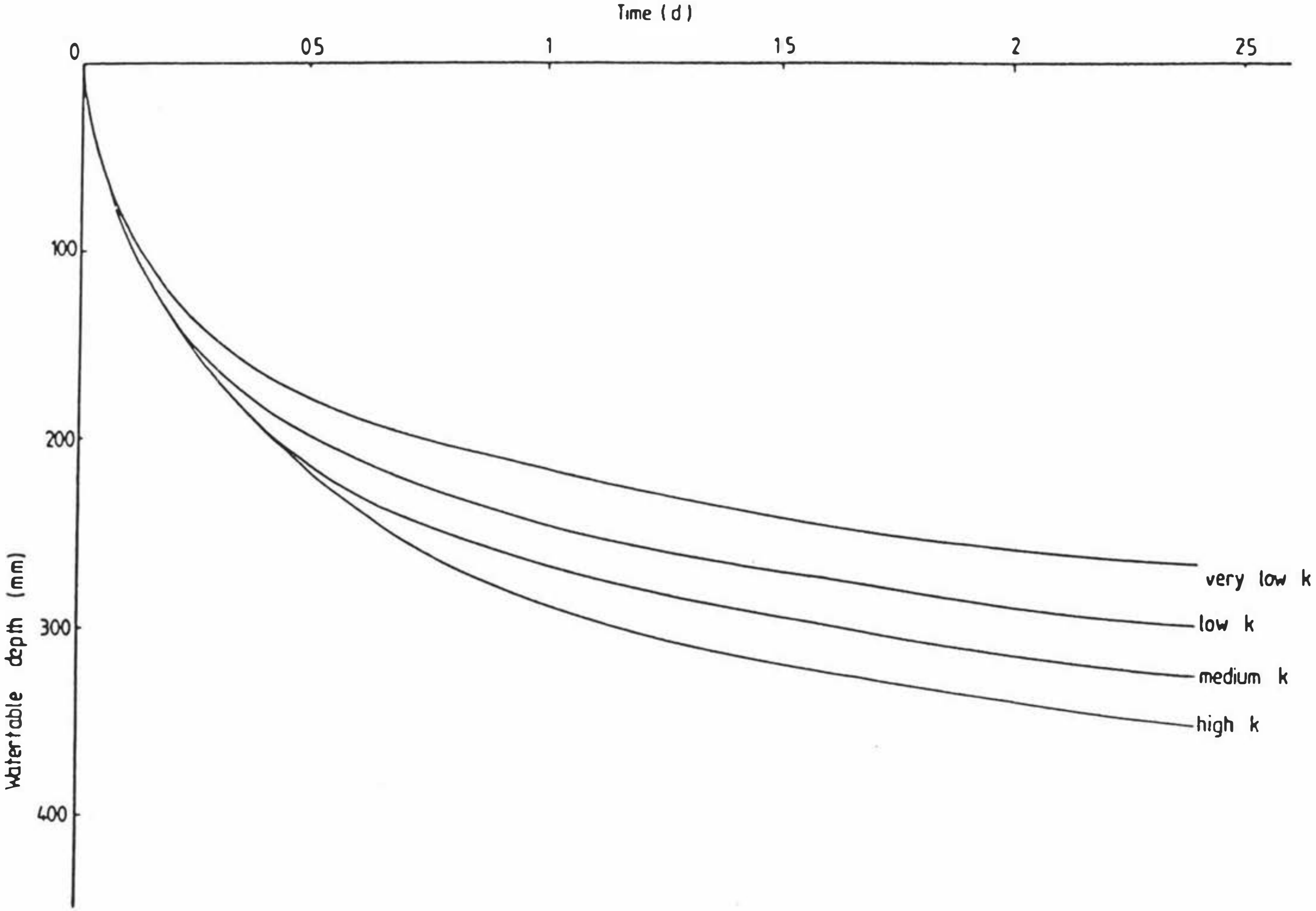


Figure 8.2 Simulation of the effect of varying the hydraulic conductivity on the fall of the watertable from the soil surface. A drainage coefficient of 10 mm d^{-1} and an evapotranspiration rate of 1 mm d^{-1} have been assumed .

the soil surface.

The line labelled 'medium' in the figure represents the decline of the watertable from the surface with the hydraulic conductivity values used in Chapter 7. When these values of K_A and K_B were doubled, halved, and quartered they were termed 'high', 'low' and 'very low', respectively.

Over the range of values assumed, K_A and K_B have relatively little effect on the time taken for the watertable to reach a depth of 200 mm, given a drainage coefficient of 10 mm d^{-1}. It would take a soil with 'low' conductivity values less than 2 hours longer to drain to a level of 200 mm than it would a soil with 'high' values. The time taken for a soil with 'very low' conductivity values to drain the watertable to a level of 200 mm is approximately twice the time taken in a soil with 'high' conductivity. However, this difference is not large when compared with the eight fold difference in the magnitude of the conductivities. As mentioned in Section 7.5.3, if the drainage coefficient was much greater than 10 mm d^{-1}, then varying the value of the hydraulic conductivity would have a far greater effect on the rate at which the watertable fell from the surface.

8.2.3 Effect of varying the mole spacing (s)

The predicted effect of varying the mole spacing on the rate of decline of the watertable from the soil surface is seen in Fig. 8.3. One surprising conclusion to be drawn from the figure is that a mole spacing of 1000 mm is no more effective at lowering the watertable to a depth of 200 mm than is a mole spacing of 2000 mm. This is because a drainage coefficient of 10 mm d^{-1} limits the rate of drainage to the carrying capacity of the drains until the watertable reaches a level of 215 mm for both the 1000 mm and 2000 mm mole spacings.

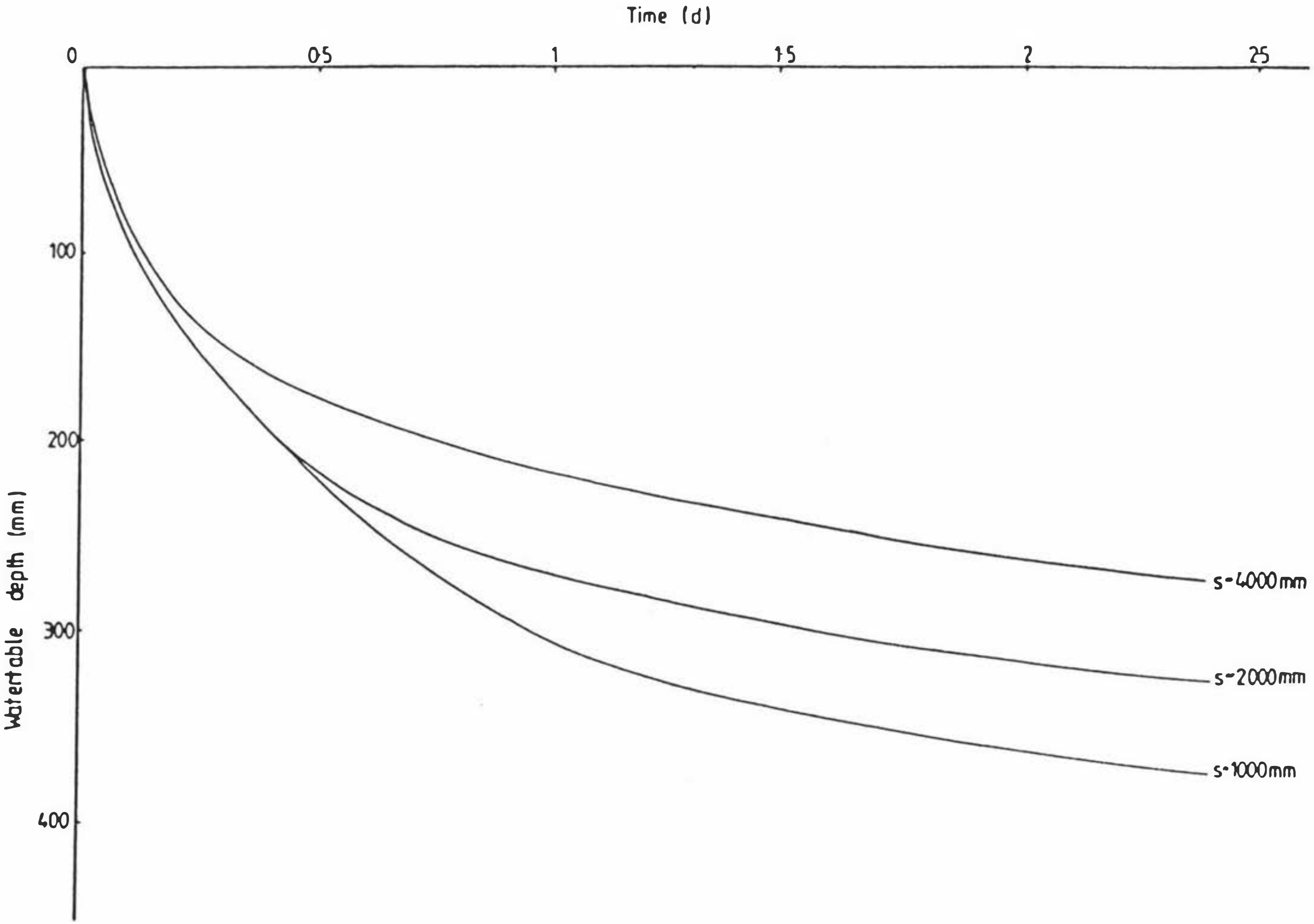


Figure 8.3 Simulation of the effect of varying drain spacing (s) on the fall of the watertable from the soil surface. A drainage coefficient of 10 mm d^{-1} and an evapotranspiration rate of 1 mm d^{-1} have been assumed .

Hence, the profiles of watertable decline for both mole spacings are similar up to this point.

After the watertable reaches a level of 215 mm in the soil with a mole spacing of 2000 mm, the drains no longer flow at the drainage coefficient, as illustrated in Fig. 8.4. The rate of drainage is then limited by the speed with which water can move through the soil towards the mole. For a mole spacing of 1000 mm the pipes flow at maximum capacity, for another 0.3 of a day after maximum flow ceases for the 2000 mm spacing. The difference in the rate of watertable decline from a depth of 215 mm, for spacings of 1000 mm and 2000 mm, is due to the diminishing gradient on the watertable as it drops further down the soil profile. In the B horizon, where water movement to the mole is impeded and the watertable profile is flatter, water will be able to drain more quickly if the moles are closely spaced. Any effect that closer mole spacings has on the hydraulic conductivity is ignored in this analysis. Such changes in conductivity are likely to mean that closer mole spacings are somewhat more effective at lowering the watertable than the analysis suggests. However, to realise the benefits of closer moles, closer spaced and/or larger pipes would be needed to increase the drainage coefficient.

Doubling the mole spacing to 4000 mm would have an adverse effect on the rate at which the watertable falls from the surface. A mole spacing of 4000 mm would take about 9 hours longer than 1000 mm and 2000 mm spacings to drop the watertable to a level 200 mm below the soil surface. As discussed, this difference in watertable levels for different mole spacings becomes more marked the deeper in the profile the watertables are, as they fall closer to the less permeable B horizon where the watertable has a small gradient and so water movement from the soil to the mole is slow.

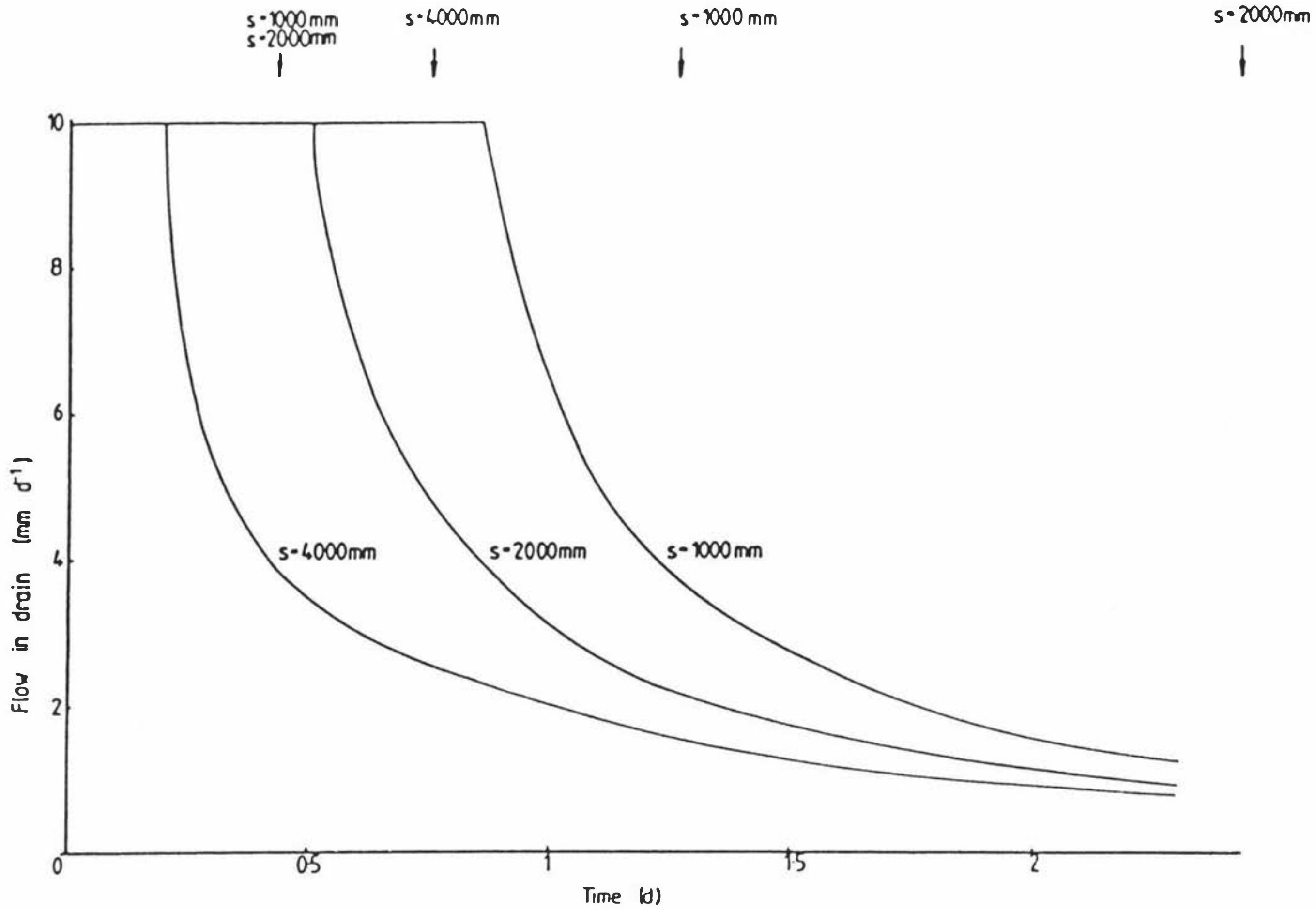


Figure 8.4 Simulation of the effect of varying drain spacing (s) on flow in the drains. Also shown is the time taken for the watertable to reach a depth of 200 mm (↓) and 325 mm (⇩) for the different drain spacings. A drainage coefficient of 10 mm d^{-1} and an evapotranspiration rate of 1 mm d^{-1} have been assumed.

One implication of these findings is that 2000 mm would appear to be an optimum spacing for mole drains for a drainage coefficient of 10 mm d^{-1}. There would be little advantage, in terms of when grazing could begin following heavy rain, in having a spacing less than 2000 mm. However, a mole spacing greater than 2000 mm will be slower in lowering the watertable to a level of 200 mm, delaying the commencement of safe grazing. However, as concluded in Chapter 3, closer mole drain spacings are effective at lowering the watertable below 200 mm more quickly.

8.2.4 Effect of varying the rate of evapotranspiration (E)

It has already been indicated in Fig. 7.4 that the model is quite sensitive to the evapotranspiration rate. This is further illustrated in Fig. 8.5, which shows the effect of varying the rate of evapotranspiration on the watertable decline for both drained (drainage coefficient = 10 mm d^{-1}) and undrained soil (drainage coefficient = 0). For the undrained soil, the effect of varying its rate is very marked, as would be expected because evapotranspiration is the only means by which water is removed from the profile. Comparison of the rate of decline of the watertable from the soil surface with 1 mm d^{-1} evapotranspiration and 3 mm d^{-1} evapotranspiration (typical winter and late spring values respectively) shows how important 2 extra millimetres of evapotranspiration a day can be to the lowering of the watertable.

If the watertable was at the surface on an undrained soil and there were 3 mm d^{-1} of evapotranspiration, then pasture on this soil could be grazed safely 1.6 days after heavy rain. If however, the evapotranspiration rate was only 1 mm d^{-1}, then 4.8 days would have to elapse before sheep could be safely allowed onto the undrained paddock. In spring such differences in the evapotranspiration rates might be

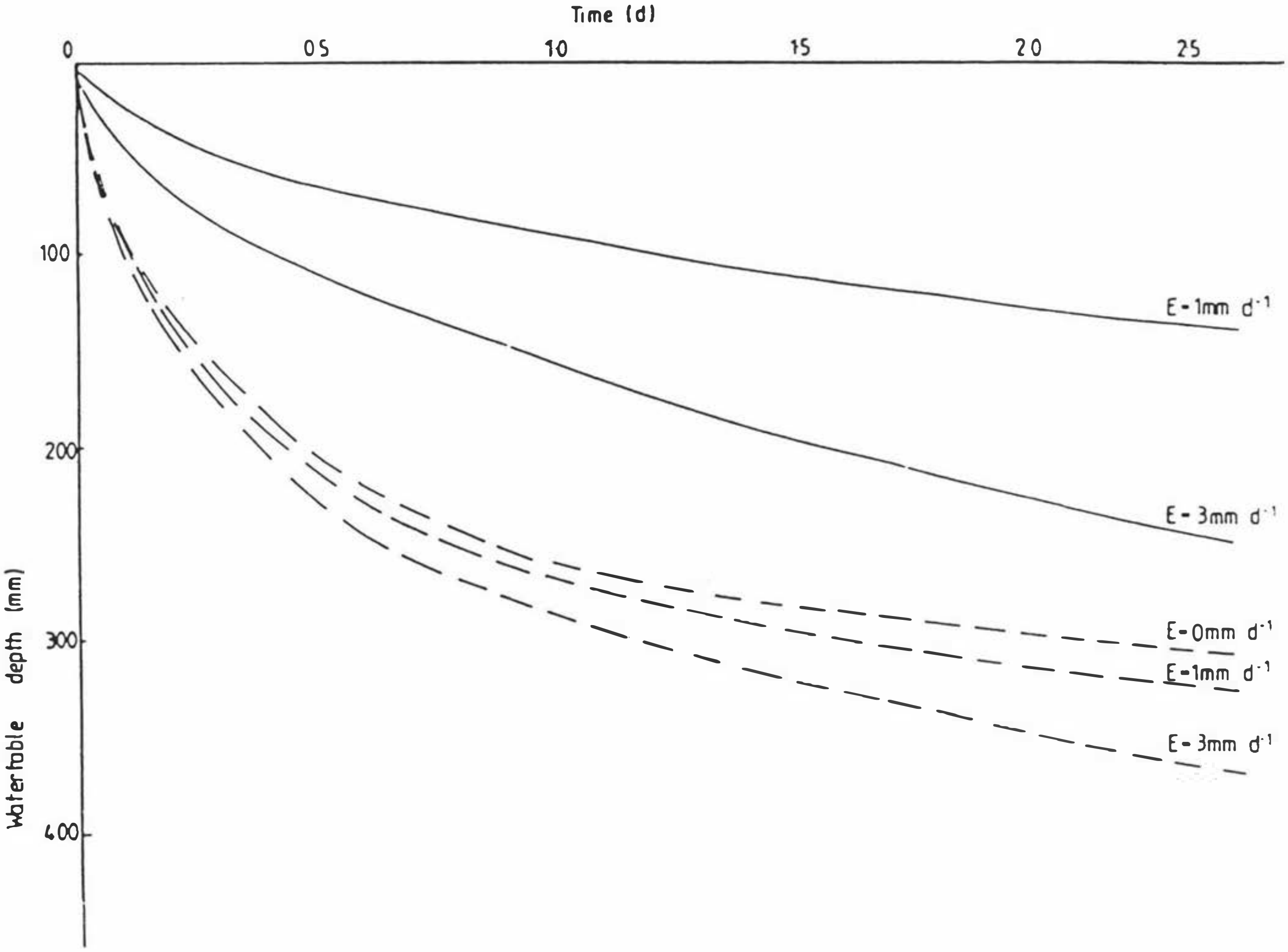


Figure 8.5 Simulation of the effect of varying the evapotranspiration rate (E) on the fall of the watertable from the soil surface for drained (·----) and undrained (———) soil. For the drained soil a drainage coefficient of 10 mm d^{-1} has been assumed .

quite common. For example, a cold cloudy spell following heavy rain could prevent the grazing of pasture for 5 days; pasture that might well have been grazed a day or so after the cessation of rain had climatic factors been more favourable.

Mole drainage very rapidly removes water from the profile, so that the effect of varying the rate of evapotranspiration is lessened in the drained soil. Changing the evapotranspiration rate has little effect on the time it takes for the watertable to fall from the surface to a level of 200 mm.

Evapotranspiration is, however, important in removing water from deeper in the profile. The permeability in the A horizon is high enough for excess water to quickly make its way to the mole drains, but when the watertable reaches the B horizon where the permeability is an order of magnitude smaller and the watertable gradient flatter, the rapid downward progress of the watertable is curtailed. It is then that water removal by evapotranspiration becomes important in lowering the watertable. After 2.4 days the watertable level for an evapotranspiration rate of 3 mm d^{-1} is 60 mm lower than that for an evapotranspiration rate of zero. Note also, that the curves representing rates of 0 and 1 mm d^{-1} have flattened out, whereas the curve for 3 mm d^{-1} is still sloping downwards indicating that the difference between the curves will increase as the watertable drops even further into the profile.

These points are summarized in Fig. 8.6, which is a plot of the equivalent depths of water leaving the soil profile by drainage and evapotranspiration. We see that, initially, the greater proportion of the water leaving the profile is exiting via the mole drains. For the first 0.5 of a day the amount of water that has left the profile as evapotranspiration is small when compared with that which has left as

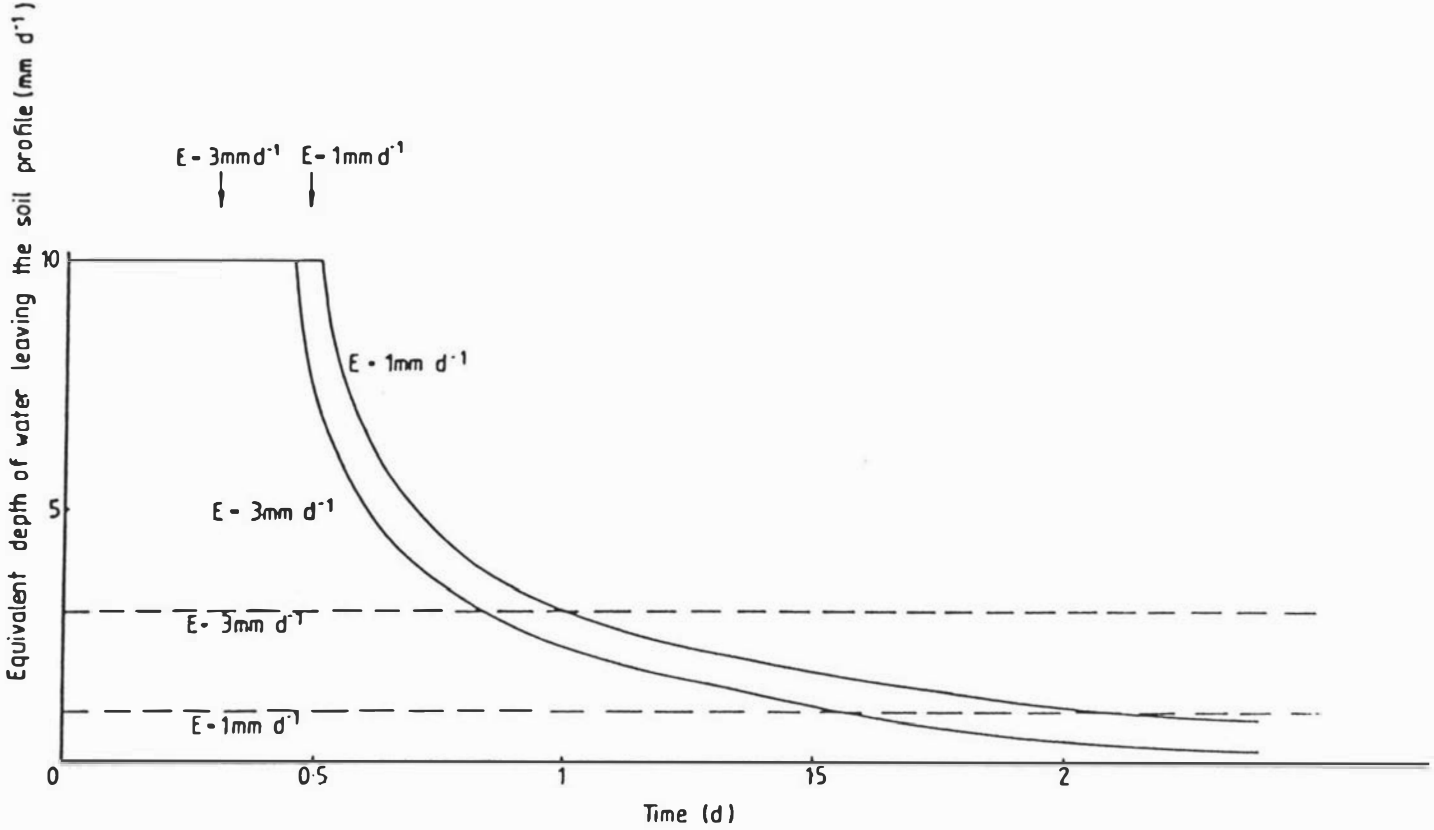


Figure 8.6 Simulation of water leaving the drained soil profile as drainage (——) and evapotranspiration (- - -). Also shown is the time taken for the watertable to reach a depth of 200 mm (↓) for different evapotranspiration rates. A drainage coefficient of 10 mm d^{-1} has been assumed .

mole drainage, hence the watertables decline at similar rates for both evapotranspiration values until this time. After 0.5 of a day the rate of flow in the drains begins to decrease and so evapotranspiration becomes a more significant factor in the lowering of the watertable. If the evapotranspiration rate is 3 mm d^{-1}, then after the first day evapotranspiration is already removing more water than subsurface drainage. Evapotranspiration is therefore an important factor in the removal of water from the drained soil profile when the watertable is in the B horizon.

8.2.5 Effect of varying the drainage coefficient (I)

The effect of varying the drainage coefficient is illustrated in Fig. 8.7, where four different drainage coefficients are considered. The line drawn for a drainage coefficient of zero represents the declining watertable on the undrained soil. The large difference between this line and those for drainage coefficients of 5, 10 and 20 mm d^{-1} illustrates the efficiency of pipe-mole drainage in lowering the watertable.

If the drainage coefficient is changed from 10 mm d^{-1} to 20 mm d^{-1}, there is a 4 hour difference in the time it takes for the watertable to drop from the surface to a depth of 200 mm. A drainage coefficient of 20 mm d^{-1} allows drainage to take place more rapidly because the pipe bearing capacity has been doubled and it will, therefore, be able to conduct away water more quickly. For a drainage coefficient of 10 mm d^{-1}, the volume of water the drains can remove from the soil will be restricted for a longer period (0.52 d) by the drains' maximum carrying capacity than for the coefficient of 20 mm d^{-1} (0.2 d).

After about 0.8 d there is very little difference in the level of the watertable for a drainage system with coefficients of 10 and 20 mm d^{-1}.

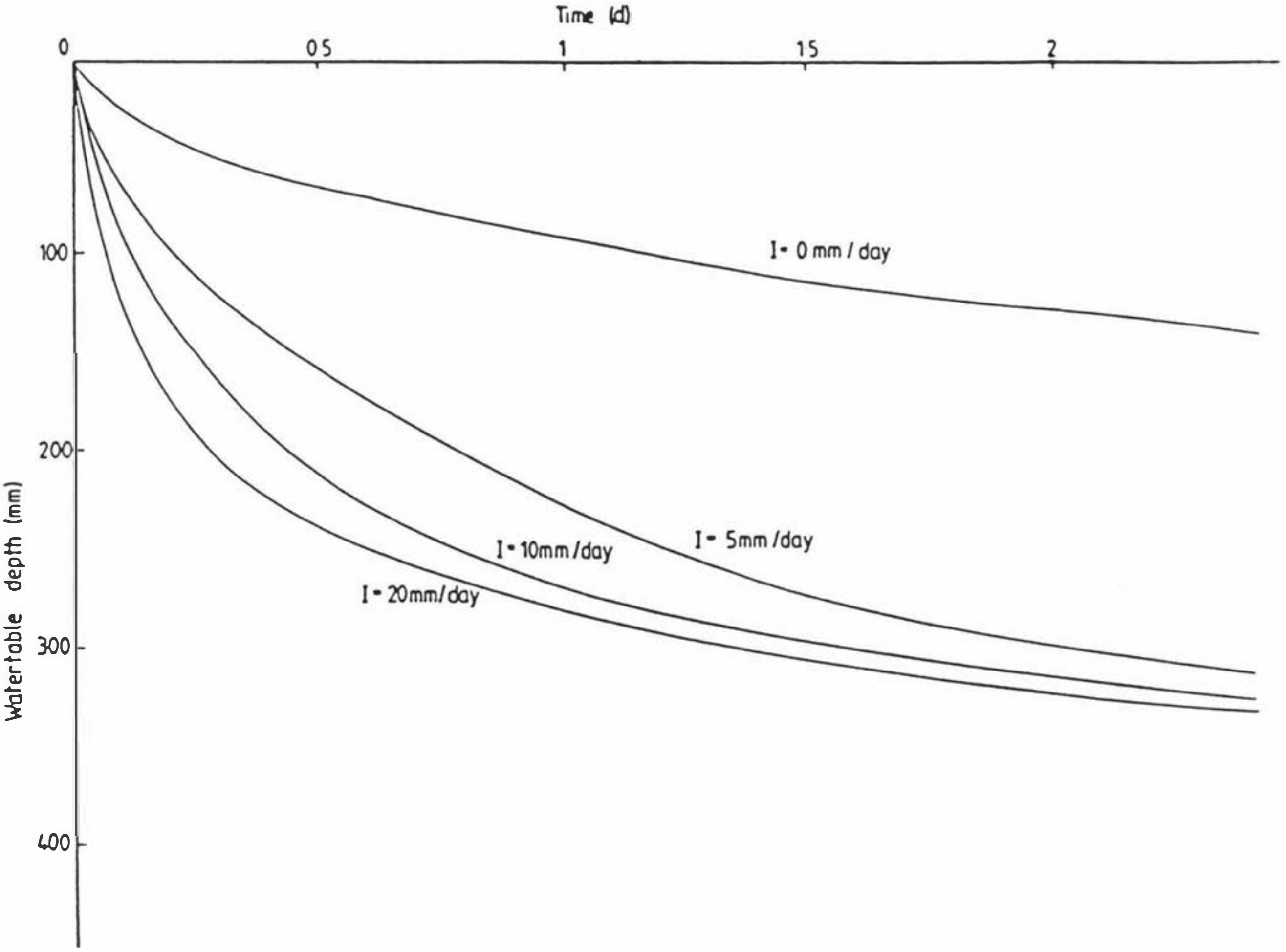


Figure 8.7 Simulation of the effect of varying the drainage coefficient (I) on the fall of the watertable from the soil surface. An evapotranspiration rate of 1 mm d^{-1} has been assumed .

This means that the rate limiting factor in the drainage process is not now the drains' ability to conduct the water away, because flow in the drains is no longer at maximum capacity, but rather the slowness with which the water makes its way through the soil towards the mole.

The above points are illustrated more clearly in Fig. 8.8, a graph of the flow rate in the drains. For the first part of the day more water (twice as much for the first 0.2 of a day) is able to flow through the drains with a drainage coefficient of 20 rather than 10 mm d^{-1}. This greater quantity of water flows in the drains until the movement of water along the flatter watertable gradient in the B horizon to the mole becomes the rate determining step in the drainage process. The drains with the smaller drainage coefficient flow at maximum capacity for a longer period so that after 24 hours roughly equal amounts of water have been drained (7.3 mm for a drainage coefficient of 10 mm d^{-1} as opposed to 7.9 mm for a coefficient of 20 mm d^{-1}).

If the drainage coefficient is only 5 mm d^{-1}, then the watertable is not lowered from the surface to a level of 200 mm until some 8 hours later than for a drainage coefficient of 10 mm d^{-1} (Fig. 8.7). This is to be expected, because as discussed above, the amount of water draining from the soil will be severely limited by the small carrying capacity of the pipe system. This limitation on drainage would be in force for a long period (1.2 days) causing the watertable to remain close to the surface for longer intervals than it would for greater drainage coefficients (Fig. 8.8).

In summary, it may be said that for a drainage system being designed for pastoral land on Tokomaru silt loam, little difference is apparent between drainage coefficients of 10 and 20 mm d^{-1}. However, a system installed to allow for the removal of only 5 mm d^{-1} may be unnecessarily slow in lowering the watertable to a depth of 200 mm so that safe grazing might commence.

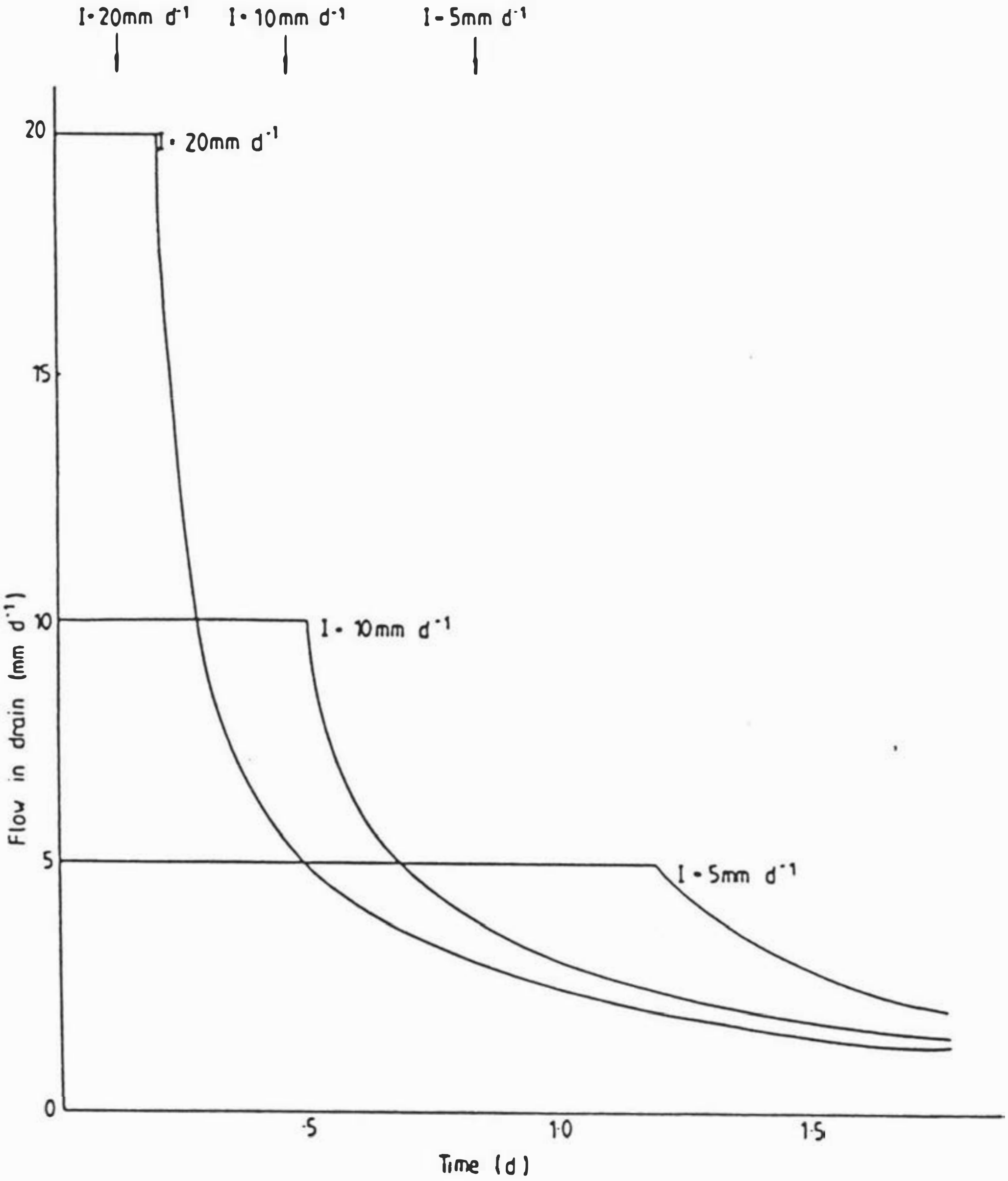


Figure 8.8 Simulation of the effect of varying the drainage coefficient on the rate of flow in the drains. Also shown is the time taken for the watertable to reach a depth of 200 mm (↓) for different drainage coefficients. An evapotranspiration rate of 1 mm d^{-1} has been assumed .

8.2.6 Effect of varying soil water retentivity (a_i)

It is possible to use the model to study the decline of the watertable from the soil surface for a soil with different soil water retentivity characteristics. To do this the a_i values, as defined in Section 7.3.1, were varied. This may be thought of as effectively changing the drainable porosity of the soil. For simplicity, it is assumed that the saturated hydraulic conductivity is primarily dependent on the presence of structural cracks and large macropores which form only a small part of the macroporosity. Thus, K and a_i are treated as independent of each other.

The result of varying a_i on the decline of the watertable is depicted in Fig. 8.9. The line labelled 'medium' in the figure is for a soil with the retentivity characteristics considered in Chapter 7. The values of a_i were then doubled and halved and termed 'large' and 'small' respectfully. For a soil with a 'large' drainable porosity, the watertable reaches a level of 200 mm from the soil surface 10.5 hours after this level is reached by the soil with a 'medium' drainable porosity. A soil with a 'small' drainable porosity reaches the level of 200 mm 5 hours before the 'medium' soil. This is to be expected, as there is less water to be drained from the soil with the 'small' drainable porosity. On the other hand, the soil with the 'large' drainable porosity, has to lose a great deal more water and the watertable will therefore decline more slowly. Drainage from this soil will be restricted for longer periods (about a day) by the drainage coefficient as there is such a large volume of water to conduct away. This point is borne out in Fig. 8.10, a graph of the effect of changing the value of a_i on the rate of flow in the drain. It is evident, that the flow rate in the drain decreases markedly with time with a decrease in the value of a_i.

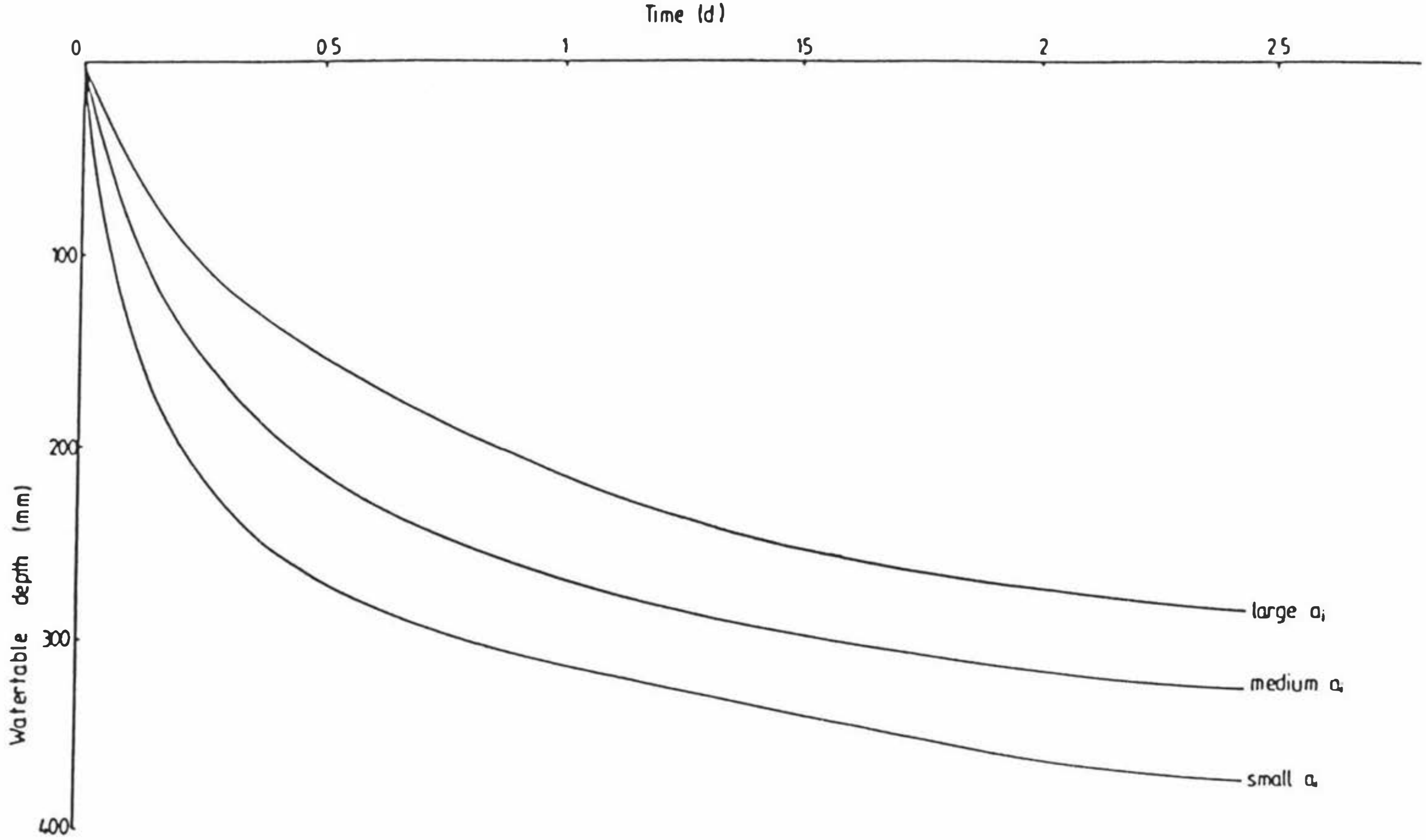


Figure 8.9 Simulation of the effect of varying the values of a_i on the fall of the watertable from the soil surface. A drainage coefficient of 10 mm d^{-1} and an evapotranspiration rate of 1 mm d^{-1} have been assumed .

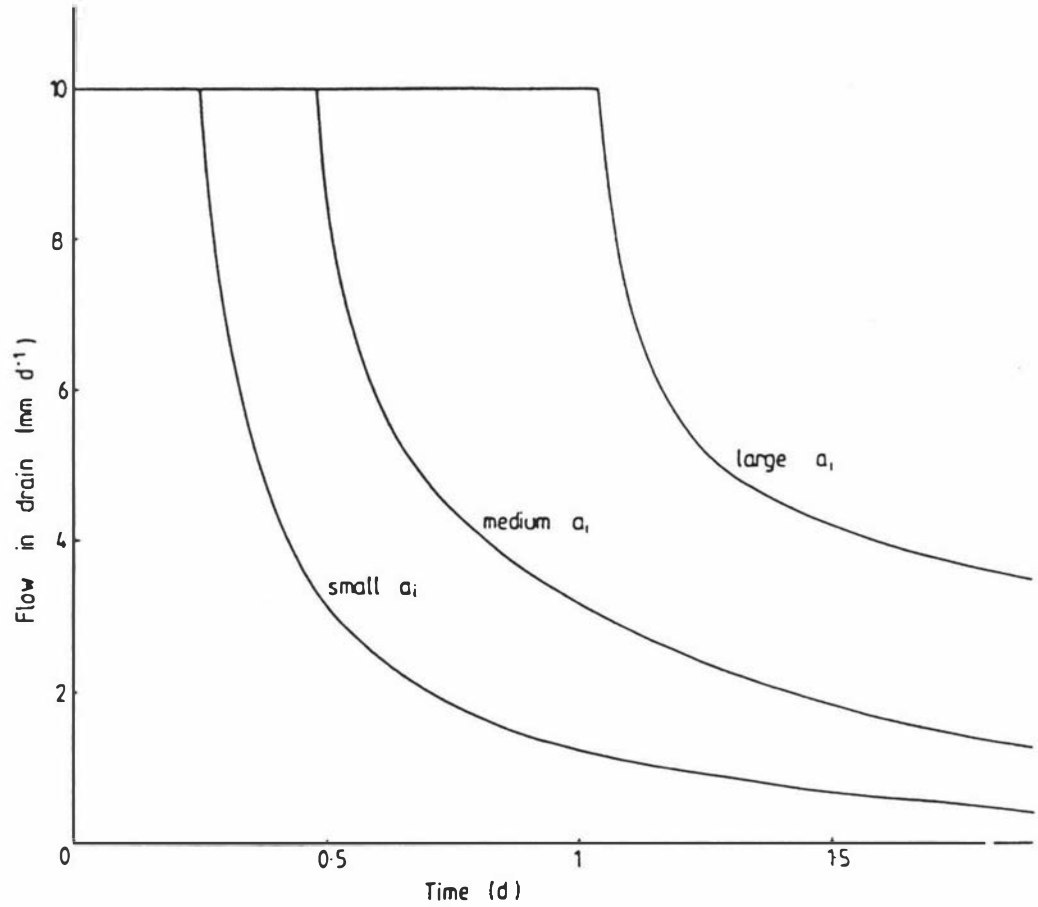


Figure 8.10 Simulation of the effect of varying the value of a_i on the rate of flow in the drains. A drainage coefficient of 10 mm d^{-1} and an evapotranspiration rate of 1 mm d^{-1} have been assumed .

The watertable in a soil with a 'small' drainable porosity falls from the soil surface more quickly than in a soil with a 'large' drainable porosity. Conversely, when it next rains, the watertable will rise more quickly in the soil with a low drainable porosity. This is evident in Fig. 8.11, a plot of the equivalent depth of water that has left the profile as drainage. We see that after 24 hours only 4.2 mm of water has drained from the soil with the 'small' drainable porosity compared with 10 mm for the soil with the 'large' drainable porosity. Any further rainfall will cause the watertable in the soil with the 'small' drainable porosity to rise to the surface much more rapidly than the soil with the 'large' drainable porosity. If sheep were grazing on a soil with small a_i values and rain fell, causing the watertable to rise quickly to be in close proximity to the surface, then damage might well be done to the pasture and soil before the stock could be moved. The same amount of rain falling on a soil with the large a_i values could be absorbed in the soil without the watertable rising up the profile to the same extent. As a result the onset of unsafe grazing would be delayed.

8.2.7 Comparison of the volume of water leaving the soil as surface runoff (S) with that leaving as drainage (L)

It is thought by some that the draining of large areas of land can overload both natural and man-made waterways. Some concern has been expressed at the possibility of increased mole drainage inducing flooding and causing damage to these waterways. The model was used to predict drainage and surface runoff after rain, and to compare the daily volume of water leaving an undrained soil with that leaving a drained soil.

Fig. 8.12 is a graph of the equivalent depth of water leaving the soil as both drainage and surface runoff for part of the winter-spring period of

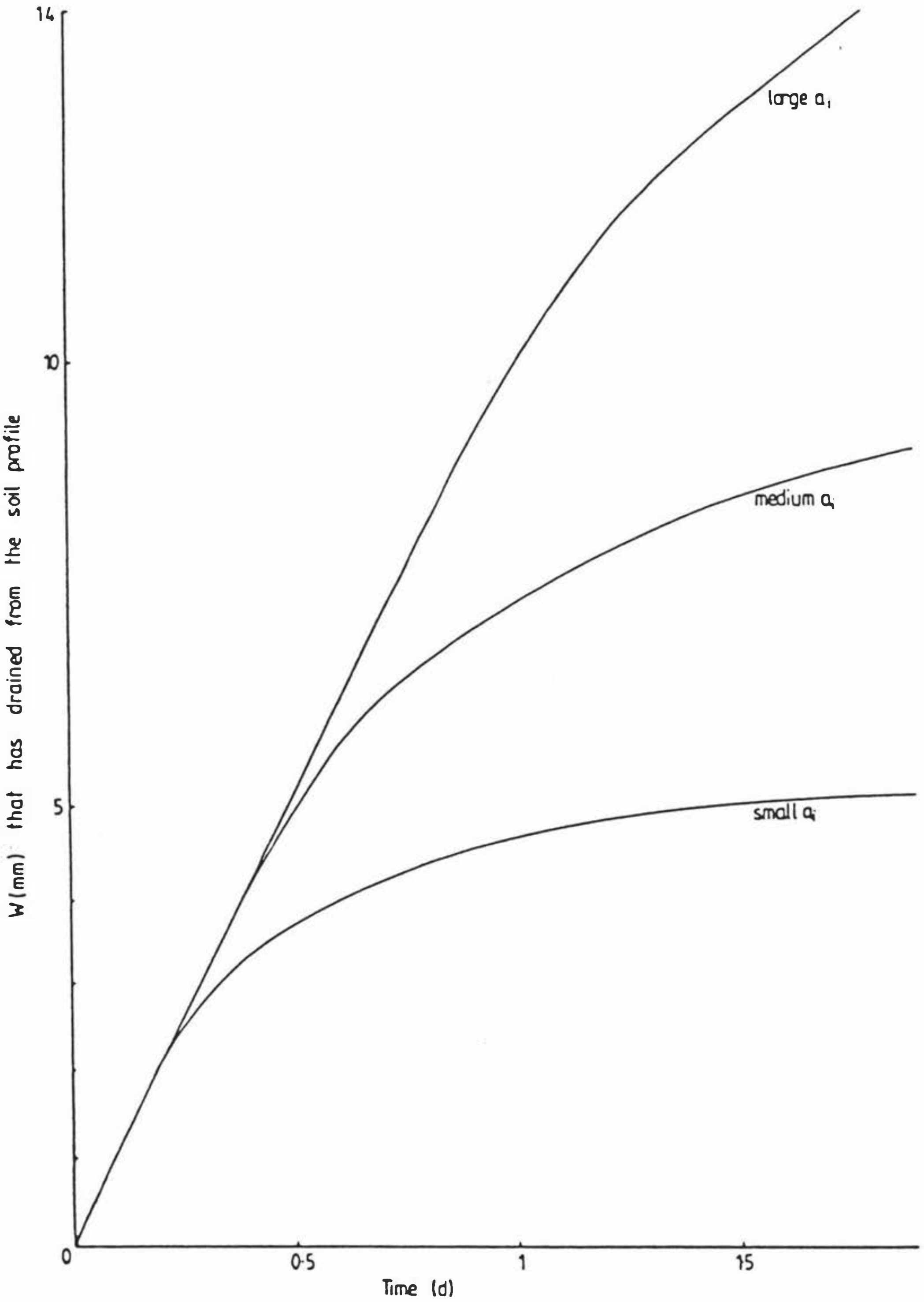


Figure 8.11 Simulation of the effect of varying the values of a_i on the amount of water that has left the soil as the watertable falls from the soil surface. A drainage coefficient of 10 mm d^{-1} and an evapotranspiration rate of 1 mm d^{-1} have been assumed.

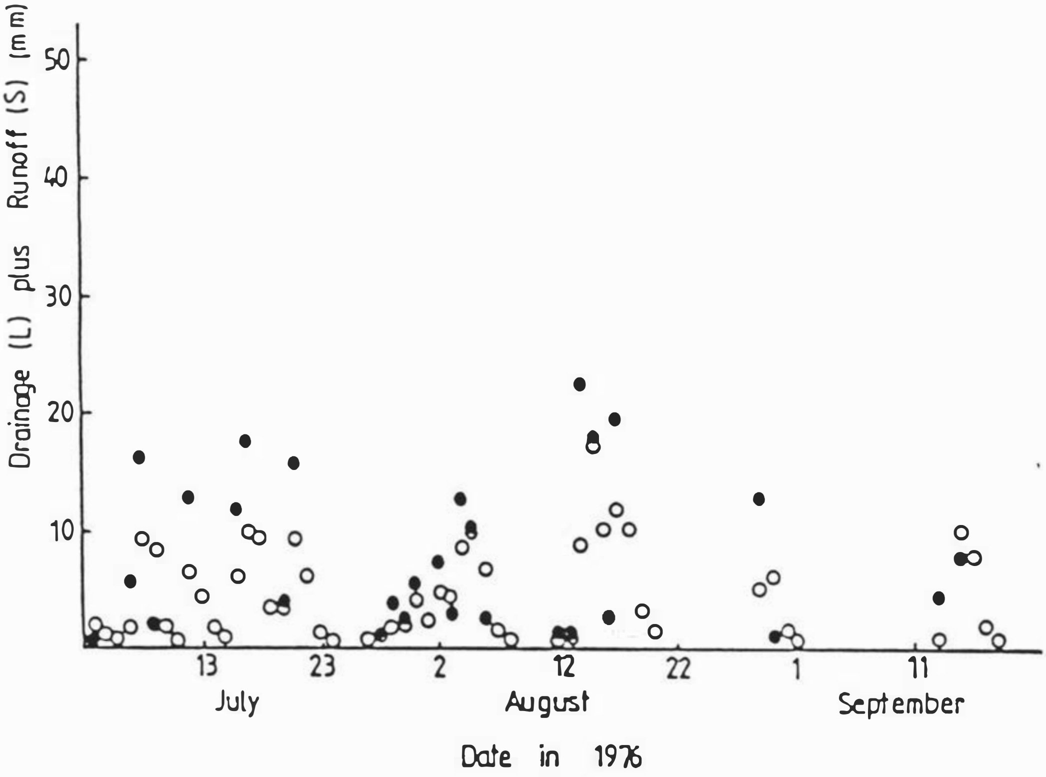


Figure 8.12 Simulation of the equivalent depth of water per day (W) leaving drained soil (O) as drainage and surface runoff and undrained soil (●) as surface runoff in 1976 .

1976. Given that the profile water contents at the start and end of the period are similar, and similar evapotranspiration rates, conservation of mass dictates that the total quantity of water leaving the drained soil as both subsurface drainage and surface runoff must be similar to the quantity of water leaving the undrained soil as surface runoff. Subsurface drainage conducts water away quickly, causing the watertable to fall, which in turn allows incoming rainfall to be stored temporarily in the profile. For undrained soil, the watertable often remains close to the soil surface, so that soon after rain starts the watertable rises to a level 2 mm above the soil surface and surface runoff begins. This means that excess water will leave the undrained plot almost as quickly as it arrives, giving the large values for surface runoff on certain days of heavy rainfall. As the drained soil can absorb and temporarily store rain water, and then conduct it away in the drains, it does not have such high discharges on days of heavy rainfall. The drains operate so as to convey water away for approximately two days after rainfall stops, gradually lowering the watertable so that the soil might absorb further rain.

The net result is that drainage releases water to the waterways in a more even manner over a period of three or four days, whereas, excess water leaving the undrained soil does so in one day. Water flowing in a drain is likely to be conducted fairly quickly to a waterway. It might be argued, that some surface runoff does not go directly to a waterway but can accumulate in low-lying areas, however, most surface runoff also rapidly reaches a waterway.

Whatever the path by which the water gets to the waterway, the model serves to illustrate the point that for any heavy late-winter or spring rainfall event, drainage removes in total approximately the same volume of water from the soil as that which runs off undrained soil.

Therefore, the total volume of water flowing in waterways cannot be markedly increased by drainage. In fact, compared with undrained land where almost all the incident rainfall floods into the waterways on storm days, drainage, as seen in Fig. 8.12 can reduce by approximately 7 to 14 mm the quantity of water flowing into the waterway on very wet days.

8.3 Conclusions

The following conclusions may be drawn:

i) The model can be used to determine the effect of varying the various parameters which determine the rate at which the watertable declines from the soil surface.

ii) Initially, the rate at which the watertable declines is controlled by the drainage coefficient. When the watertable is deeper than 215 mm the rate at which the watertable declines is limited by the speed with which water can move through the soil to the mole.

iii) There are strong interactions between drainage design parameters. Changing any one parameter may not markedly alter the drainage rate. Altering two parameters simultaneously, for example, increasing the drainage coefficient and decreasing the mole spacing, may have a marked affect on the time it takes for the watertable to decline from the surface to be deep within the profile.

iv) The model shows that while mole drainage will increase the flow to catchment drains and rivers on some days, it will not increase the total flow in these drains over the winter-spring season. On days with the heaviest rainfall mole drainage will decrease the flow to waterways. Because drained land has some capacity to store or absorb incoming rain and then slowly release this excess water through its drainage system, mole drained land may in fact alleviate to some extent the adverse effects of flooding observed following surface runoff from undrained land.

CHAPTER 9

CHAPTER 9

AN OVERVIEW

In the preceding chapters, most of the claimed benefits of drainage listed in Chapter 1 have been examined. In this chapter the major points from previous chapters are discussed in context with a view to obtaining an overview of this investigation into the benefits of drainage.

In Chapter 3, mole drainage was shown to have a pronounced effect on watertable depth and on the water content of the surface soil. In Chapters 4, 5 and 6, the effects of decreasing the surface soil water content on certain soil and plant properties were examined.

The two major benefits to be gained from drainage were increased pasture utilisation during grazing when the watertable is near the surface on the undrained plots and enhanced regrowth rates subsequent to such a grazing. Pasture utilisation during mob grazing in 1983, at a stocking rate of 490 ewes ha^{-1}, was 25% lower on the undrained than on the drained plots and 35% lower when the stocking rate was 1470 ewes ha^{-1} in 1984. Not only was pasture utilisation significantly lower on undrained plots during mob grazing in winter, but it was also lower during spring under set stocking at 17 ewes ha^{-1}, with approximately 35% more dry matter left on the undrained plots. Between the mob grazing and the end of spring, growth rates on the drained plots were approximately 30% higher than on the undrained plots.

The benefits of drainage were evident only when the grazing animal was introduced into the system when the soil was wet. Therefore, the damage averted by drainage involved an animal-plant-soil interaction rather than just a plant-soil interaction. The cause of this adverse interaction when the undrained plots were grazed was probably due to the low bearing strength of the wet soil surface, which meant the hoof of the grazing sheep caused severe damage to both the undrained soil surface and the pasture growing on it. Because the water content of the surface soil on the drained plots was considerably lower than that on the undrained plots, the bearing strength was higher and treading damage to both plant and soil was kept to a minimum.

In Chapter 5, drainage was shown to have a beneficial effect on both the species and chemical composition of the sward. On the undrained plots, treading damage caused an ingress of weeds over spring, with a 3-fold increase in the incidence of weeds and a 4-fold increase in the incidence of bare ground compared with the drained plots. There was also a 2-fold decrease in the incidence of clover on the undrained plots relative to the drained plots. The difference in the incidence of weeds between drained and undrained plots was still present the following autumn. A point analysis on the 2 April 1984 revealed a 3-fold increase in the incidence of weeds on the undrained plots. An implication of these findings is that draining a waterlogged soil may well improve the botanical composition of the sward.

In November/December, there was a decrease in the amounts of N, P and S present in the grass and clover components of the sward grown on the undrained plots relative to the drained plots. There were a number of factors which may have contributed to these differences, including the greater treading damage and lower dung return on the undrained plots and the younger nature of the sward on the drained plots.

It was also found that drainage encouraged a deeper rooting system. In the winter months of relative root inactivity, drainage encouraged proliferation in the zone 40 - 80 mm from the surface with a 4- and 2-

fold increase in the relative root activity (RRA) of grass for H_2PO_4 -P and SO_4 -S respectively, and likewise a 2- and 3-fold increase in this zone for the RRA of clover. During spring, a time of greater root activity, drainage enhanced root proliferation in the zone 80 - 200 mm. For grass, RRA in this region for H_2PO_4 -P and SO_4 -S was 24% and 29% on the drained plot and 18% and 23% on the undrained plots, respectively. For clover, the RRA in the region 80 - 200 mm for H_2PO_4 -P and SO_4 -S was 22% and 27% on the drained plots and 10% and 11% on the undrained plot, respectively. The greater difference between drained and undrained plots for clover than grass shows that the root system of clover is more affected by drainage.

One advantage of having a root network which proliferates at depth is that nutrients may be extracted from a greater volume of soil. It was suggested in Chapter 1 that the adverse effects of drought may be reduced when the root network penetrates to greater depth but as drought conditions were not experienced during this study, this claim could not be investigated.

Two of the commonly proposed benefits of drainage, namely increased soil temperature and better soil aeration, were discussed in Chapter 6. Experimental data gathered in the field showed that drainage did not increase soil temperature, and consequently the enhanced pasture growth rates observed on the drained plots could not be explained by a temperature increase. Also, although no measurements were made in this study, a review of the literature suggests that low aeration was not primarily responsible for the depressed regrowth rates measured on the undrained plots, although oxygen deficiency, following pugging, may have exacerbated the damage done during grazing.

It was observed that when the watertable was shallower than 200 mm, pugging damage to both the sward and soil occurred during grazing. It was also estimated that on a day when 10 mm or more rain fell, the soil surface would be wet enough for treading damage to occur, regardless of the depth of the watertable. Days when the watertable depth was less than 200 mm and/or 10 mm of rain fell were thus designated as "unsafe" grazing days.

By comparing the number of unsafe grazing days for drained and undrained soil in the winter-spring period for different years, an idea may be gained of the cost-effectiveness of mole drainage. It was shown in Chapter 7, with the aid of a model developed to predict watertable levels and the number of unsafe grazing days, that the benefits of drainage in a dry year (such as 1982) are minimal, with 11 unsafe grazing days being predicted on both drained and undrained soils. In contrast, for 1983 (a year of average rainfall), mole drainage caused a pronounced decrease in the number of unsafe grazing days from 69 to 10. Likewise, in a wet year, the benefits of mole drainage are easily seen with a reduction in the number of unsafe grazing days from 119 to 33. Pasture that cannot be grazed for as many as 69 days in an average year would present a major problem to farm management; a problem effectively solved by drainage.

Finally, in Chapter 8, certain parameters within the model were varied to investigate how the drainage system could be improved. The model showed that for the pipe-mole system under study, with a drainage coefficient of 10 mm d^{-1}, the carrying capacity of the pipe controls the drainage rate when the watertable is shallower than 215 mm from the soil surface. When the watertable is below this depth the drainage rate is controlled by the speed with which water moves through the soil to the mole. To increase the efficiency of mole drainage in the Tokomaru silt loam both the pipe size and mole spacing would need to be altered. This illustrates the interdependence of many of the drainage design parameters, as changing one parameter may not markedly alter the drainage rate but altering two parameters in tandem may have a marked effect.

If the drainage coefficient is doubled from 10 mm d^{-1} to 20 mm d^{-1} and the mole spacing halved to 1 m, then the watertable will decline at a more rapid rate and reach the depth of 200 mm a few hours earlier. Though this time difference may not be important for pastoral farming, it may well be crucial on heavy textured soils for more intensive land use practices, such as cropping or for fields set aside for sports or recreational purposes.

Avenues for further investigation may include adapting the model for use on different soil types and with cattle rather than sheep. The model and the concept of safe/unsafe grazing days may also be useful to economists in predicting the likely financial benefits of drainage.

There can be little doubt that grazing a paddock on any day when the bearing strength of the soil surface is not high enough to properly support the hoof of the grazing animal will be to the detriment of both the quantity and quality of the sward. Therefore, an important part of farm management is to prevent the grazing of wet paddocks on unsafe grazing days. As an aid to this end, artificial drainage is valuable in that it is a most effective way of decreasing the frequency of such days in an average or wetter than average winter-spring period.

APPENDICES

APPENDIX A:

SOIL PROFILE DESCRIPTION

Table A.1 Profile Description of Tokomaru Silt Loam in Dairy Farm No.4, Massey University, Palmerston North (Pollok, 1975).

Horizon	Depth (cm)	Description
Ah1	0 to 10 ± 1	Silt loam; dark greyish brown (10 YR 4/2), with slight yellowish-red (5 YR 4/6, 5/6) mottling around grass roots; moderately developed fine and medium crumb structure; friable; considerable humus; numerous, fine grass roots; slightly imperfect internal drainage; moist; fairly distinct and even boundary.
Ah2	10 ± 1 to 20 ± 1	Silt loam; dark greyish brown (10 YR 4/2), with some yellowish-red (5 YR 4/6, 5/6) mottling around grass roots; moderately developed, medium crumb, coarse granular and nutty structure; friable; moderate amount of humus; numerous, fine grass roots; some earthworms; some ironstone concretions; slightly imperfect internal drainage; moist; rather indistinct, slightly uneven boundary.
AB	20 ± 1 to 26 ± 2	Silt loam; greyish brown (2.5 Y 5/2), moderately settled yellowish-red (5 YR 4/6), dark reddish brown (2.5 YR 3/4) and dusky red (10 R 3/4) in a reticulate pattern; moderately to strongly developed, medium nutty structure; friable-firm; some humus; moderate number of grass roots; some earthworms; some ironstone concretions ca 6 . in diameter; imperfect internal drainage; moist; rather indistinct, slightly uneven boundary.
Bg	26 ± 2 to 78 ± 5	Clay loam; light brownish grey (2.5 Y 6/2) and light olive grey (5 Y 6/2), with abundant, coarse, strong brown (7.5 YR 5/6) mottles arranged in a blotchy pattern, with greatest concentration towards the upper part of the horizon and sometimes developing into soft ironstone concretions; weakly to moderately developed, coarse blocky and prismatic structure; olive grey clay skins; very hard when dry, plastic and sticky when wet; some humus present in pipings from the horizon above and in the vicinity of old decaying bush roots; grass roots rare; no fauna seen; impeded internal drainage; wet; rather indistinct, somewhat uneven boundary due to weathering of the horizon beneath.
Cxg	78 ± 5 to 114 ± 3	Silt loam; colour of soil within peds light olive grey (5 Y 6/2), pale olive (5 Y 6/3) and strong brown (7.5 YR 5/6, 5/8) in a reticulated mottling pattern; colour of soil filling the cracks between peds uniform pale grey (5 Y 7/2), with a thin rusty brown band formed at the interface between crack and ped surface; strongly developed, very coarse polygonal structure (penta and hexa columnar and trapezocolumnar after Brewer, 1964) with the polygons varying from 15 to 40 cm in width and separated by large, mainly vertically oriented, soil-filled cracks 2-4 cm wide, both peds and cracks being continuous with the horizon beneath; thick clay skins; soil within peds compact and extremely hard when dry, moderately sticky and plastic when wet and dispersible in water (fragipan); virtually no humus within peds, but a little in the vicinity of decaying roots within the cracks; some old bush roots and a few more recent living roots within cracks, but virtually none within peds; no fauna seen; numerous pinhead Fe/Mn concretions within peds; impeded internal drainage, the main avenue for water movement being down the soil-filled cracks; moist; diffuse (imperceptibly merging) boundary.
Cwg1	114 ± 3 to 147 ± 1	Silt loam; colours as for horizon above, but with light olivo grey (5 Y 6/2) now assuming predominance over strong brown (7.5 YR 5/6) in the mottling pattern within peds; structure, cracks and clay skins as in the horizon above; noticeable change in consistency, with the soil becoming less hard and compact and losing the properties of a fragipan; little if any humus; no roots; no fauna seen; pinhead concretions become darker in colour (black) and more manganiferous compared with the horizon above; imperfect internal drainage with the main avenue for water movement being down the soil-filled cracks between peds; moist; distinct, even boundary.

CONTINUED

Table A.1 (continued)

Horizon	Depth (cm)	Description
Cwg2	147 ± 1 to 157 ± 1	Silt loam; light olive grey (5 Y 6/2) to olive (5 Y 5/3), moderately mottled strong brown (7.5 YR 5/6, 5/8) in reticulate pattern; moderately developed, very coarse polygonal structure (penta and hexa columnar and trapezocolumnar after Brewer, 1964), with the soil-filled cracks between structural units tending to be finer and more widely spaced compared with the Cxg and Cwg1 horizons above; firm; no humus, roots or fauna; numerous dark grey and black Fe/Mn pinhead concretions; imperfect internal drainage; moist; overlies terrace gravels at depth.

APPENDIX B:

CHEMICAL COMPOSITION OF GRASS AND CLOVER
SAMPLED BETWEEN 20 OCTOBER, 1982 AND 11 APRIL, 1983.

Table B.1 Percentage N, P and S in grass and clover for the spring-summer period of 1982/1983.

		% P		% N		% S	
Date	Treatment	Grass	Clover	Grass	Clover	Grass	Clover
20/10/82	Pipe-mole	0.41	0.43	3.56	5.15	0.36	0.23
	Mole-mole	0.39	0.44	3.43	5.17	0.36	0.25
	Undrained	0.38	0.45	3.33	5.19	0.36	0.24
15/11/82	Pipe-mole	0.40	0.39	3.01	4.86	0.28	0.23
	Mole-mole	0.36	0.37	2.85	5.06	0.33	0.25
	Undrained	0.39	0.37	2.88	4.69	0.33	0.28
8/12/82	Pipe-mole	0.41	0.41	2.47	5.28		
	Mole-mole	0.37	0.38	2.62	5.36	*	
	Undrained	0.38	0.39	2.99	5.21		
12/ 1/83	Pipe-mole	0.33	0.33	2.27	4.38		
	Mole-mole	0.35	0.33	2.37	4.35	*	
	Undrained	0.30	0.35	2.27	4.47		
11/ 4/83	Pipe-mole	0.27	0.35	2.50	4.05	0.32	0.22
	Mole-mole	0.26	0.32	2.34	4.21	0.34	0.23
	Undrained	0.31	0.35	2.41	4.32	0.37	0.21

*No analyses carried out.

APPENDIX C:

THE THERMAL PROPERTIES OF DRAINED AND UNDRAINED SOIL

D.R. Scotter

C.1 Introduction

The basic thermal properties of a soil are its thermal conductivity (K_h) and its volumetric heat capacity (c_v). Both properties vary with soil water content. The ratio of these two parameters is the thermal diffusivity ($\kappa = K_h/c_v$). Laboratory measurements of thermal diffusivity were made on intact soil cores of Tokomaru silt loam A horizon at two matric potentials, corresponding to drained and undrained soil. Measurements were made firstly at the equilibrium matric potential which would be reached when the watertable is at mole-depth (i.e. -4.5 kPa at the soil surface), and secondly at a matric potential of zero at which the soil was effectively saturated. Due to the coupled flow of heat and water vapour, the thermal diffusivity is temperature dependent in moist soil, but as de Vries (1966) has shown, at and near saturation this dependence is negligible, and so is not relevant in this study.

C.2 Materials and Methods

The method used to measure the thermal diffusivity was similar to that of Parikh et al. (1979), but was adapted so cores rather than disturbed soil could be used, and involved a different method of data analysis. Sharpened cylindrical aluminium corers, 150 mm long and with a wall thickness of 1 mm, were used to obtain topsoil cores 73.5 mm in diameter and 100 mm long. The cores were taken in July, 1984 when the soil was wet, but not saturated. The short pasture plants were left on the soil cores. After sampling the cores were drained to a matric potential of -4 kPa (in the middle of the core) using Haines' apparatus. A 4 mm thick acrylic plate was then sealed onto the bottom of each corer using rubber adhesive. A copper-constantan thermocouple was inserted axially into each core to a depth of 50 mm using a jig. Each core was then brought to temperature equilibrium at approximately 15°C in a stirred waterbath. It was then transferred quickly to another bath set at approximately 35°C and the axial temperature monitored at minute intervals until a new equilibrium was reached. The core was then returned to the 15°C bath and the temperature decline monitored.

Next the cores were weighed, and then sprayed gently and intermittently with water until a little free water remained on the surface. The cores were then reweighed and the double waterbath experiment repeated. Lastly the cores were oven-dried and reweighed.

As the thermal conductivities of aluminium and perspex are 201 and 0.2 W m^{-1} K^{-1} respectively (Tennent, 1971), all heat movement into and out of the soil cores was assumed to be radial. Also due to the thin corer walls, and the high K_h and low c_v of aluminium compared to moist soil, the temperature transient in the corer was assumed to be negligible relative to that in the soil core. That is, the assumed boundary conditions for the soil were

$$\begin{aligned} v &= v_o \qquad t < 0, \quad 0 \leqslant r \leqslant a \\ v &= v_1 \qquad t \geqslant 0, \quad r = a \end{aligned} \qquad (C.1)$$

where v is temperature, t is time, r is radial distance, a is the radius of the soil core, and v_o and v_1 are the initial and imposed temperatures respectively.

The form of the diffusion equation applicable to transient radial heat conduction is

$$\frac{\partial v}{\partial t} = \kappa \cdot \left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r}\right) \qquad (C.2)$$

The solution of equation (C.2) subject to (C.1) for the axial dimensionless temperature at $r = 0$ follows from equation (10) on page 199 of Carslaw and Jaeger (1959). It is

$$V = 1 - 2\sum_{n=1}^{\infty} \exp(-\beta_n^2 \Xi)/\beta_n J_1(\beta_n) \qquad (C.3)$$

where $V = (v - v_o)/(v_1 - v_o)$, β_n is the n^{th} root of $J_o(\beta_n) = 0$, J_o and J_1 are Bessel functions of the first kind and integer order 0 and 1 respectively, and $\Xi = \kappa t/a^2$. For $\Xi > 0.15$, only the first two terms of the series solution are significant and the equation may be evaluated by noting $\beta_1 = 2.405$, $\beta_2 = 5.520$, $J_1(\beta_1) = 0.519$ and $J_1(\beta_2) = -0.340$. A graph of the functional relationship between V and Ξ from equation (C.3) is shown in Fig. C.1. For each experiment the thermal diffusivity is conveniently found from the time at which $V = 0.5$ (denoted to $t_{0.5}$) as

$$\kappa = 0.201\, a^2/t_{0.5} \qquad (C.4)$$

C.3 Results and Discussion

Six cores were analysed but data from one core were rejected as that core needed 50% more water to saturate it than did the other five. Later investigation showed an earthworm had burrowed extensively in the soil adjacent to the aluminium corer after the core had been taken. The average mass of oven-dry soil in the five cores was 414 ± 15 g, and the water added to bring the moist cores to saturation was 24.9 ± 1.5 g. Their gravimetric water

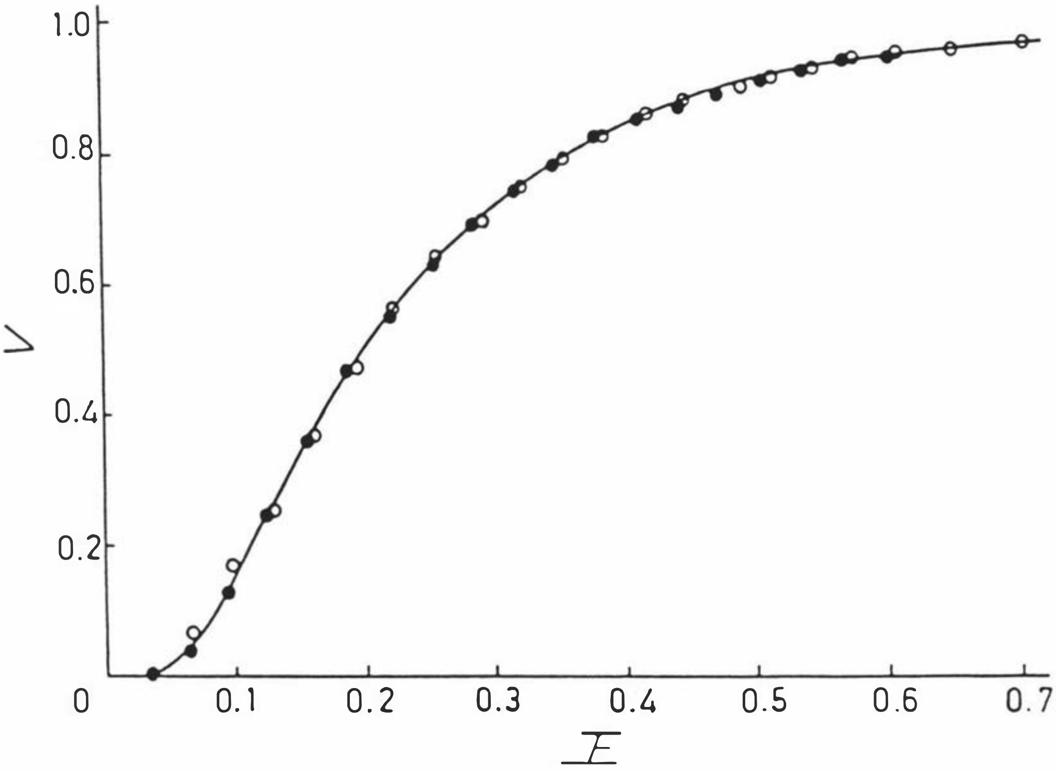


Figure C.1 Dimensionless temperature as a function of dimensionless time during laboratory thermal diffusivity measurements. The line is equation (C.3) and the data points are for one of the cores during warming (●) and cooling (○) .

content at a matric potential of −4 kPa was 0.549 ± 0.009, and at saturation it was 0.609 ± 0.010.

The bulk density and volume fractions of the cores were calculated, assuming 6% of the dry mass was organic matter with a particle density of 1.4 Mg m^{-3}, and that the rest was inorganic material with a particle density of 2.65 Mg m^{-3}. This gave volume fractions for inorganic and organic solids of 0.38 and 0.04 respectively, and a bulk density of 0.95 Mg m^{-3}. This means that the two volumetric water contents at which the thermal diffusivity was measured were 0.52 and 0.58.

Fig. C.1 shows the measured and assumed relationship between V and E for one of the cores. The data for cooling and warming are almost coincident, and fit closely the theoretical curve from equation (C.3). This agreement confirms that the assumed boundary conditions were closely approximated in the experiment.

The thermal diffusivity measured at a matric potential of −4 kPa was 0.358 ± 0.012 $mm^2\ s^{-1}$. The value measured after the cores were saturated was almost identical, 0.362 ± 0.013 $mm^2\ s^{-1}$. Values obtained by warming and cooling the cores agreed closely, differing on average by only 0.01 $mm^2\ s^{-1}$.

The volumetric heat capacity may be calculated as (de Vries, 1966)

$$c_v = c_m\Theta_m + c_o\Theta_o + c_w\Theta_w \qquad (C.5)$$

where Θ_m, Θ_o and Θ_w are the volume fractions of soil minerals, organic matter and water respectively. In the equation c_m, c_o and c_w are the volumetric specific heats of inorganic soil material, organic matter and water, with values of 1.9, 2.5 and 4.2 MJ m^{-3} K^{-1} respectively. The calculated values for c_v are 3.1 MJ m^{-3} K^{-1} for the soil at −4 kPa, and 3.3 MJ m^{-3} K^{-1} for the saturated soil.

From κ and c_v, the thermal conductivity of the soil is then calculated as 1.1 W m^{-1} K^{-1} at -4 kPa and 1.2 W m^{-1} K^{-1} at saturation.

The observed constancy of the thermal diffusivity with increasing water content near saturation deserves comment, as it contrasts with the commonly reported decline (Marshall and Holmes, 1979). However disturbed soil has been used in most other studies, compared to the intact soil cores used here. It is likely that differences in macropore geometry cause the thermal conductivity, and so thermal diffusivity, of intact and disturbed soil to respond differently to changes in water content near saturation.

APPENDIX D:

SIMULATION OF THE DECLINE OF THE WATERTABLE WITH TRANSIENT FLOW IN THE UNSATURATED ZONE

D.R. Scotter

The model presented in Chapter 7 assumes that the water in the soil above the watertable is always in potential equilibrium with the watertable. That is, the absolute value of the pressure potential at any point equals the height above the watertable. A numerical analysis of profile drainage was undertaken to examine the validity of this assumption. Vertical drainage at a rate of 10 mm d^{-1} from an initially saturated soil was modelled. A watertable decline from the surface to 300 mm depth was considered and the soil hydraulic properties were taken as uniform over this depth interval.

The relationship between volumetric water content (Θ) and pressure potential (P) assumed was

$$\Theta = 0.00019P + 0.486 \qquad (D.1)$$

where P has units of mm of water.

The saturated hydraulic conductivity was taken as 372 mm d^{-1}. Scotter and Kanchanasut (1981) measured a mean unsaturated hydraulic conductivity at P = − 200 mm of 11 mm d^{-1} in large cores of Tokomaru silt loam A horizon. Assuming the unsaturated hydraulic conductivity (k) varies exponentially with volumetric water content, it follows from these two conductivity values and equation (D.1) that

$$k = 10^{-17} \exp(92.6\Theta) \quad (\text{mm d}^{-1}). \qquad (D.2)$$

The finite difference forms of Darcy's law for vertical flow (equation (7.5) of Chapter 7) and the appropriate continuity equation

$$\partial q/\partial t = -\partial\Theta/\partial z \qquad (D.3)$$

where q is the flux density, were then solved numerically. A depth interval of 10 mm, and a time interval of 10^{-4} days were used in the numerical analysis. The approach used was similar to that of Hillel (1977), except that a Sinclair Spectrum microcomputer and BASIC were used, rather than a mainfram computer and CSMP. A listing of the program and a sample printout appear in Fig. D.1. The main symbols used in the program are defined in Table D.1.

If potential equilibrium is assumed to occur in the soil above the watertable during drainage, then

$$P = z - T. \qquad (D.4)$$

The equivalent depth of water in a profile 300 mm deep (W) is given by

$$W = \int_0^T \Theta \, dz + \int_T^{300} \Theta \, dz. \qquad (D.5)$$

Substitution of equations (D.1) and (D.4) and integration gives

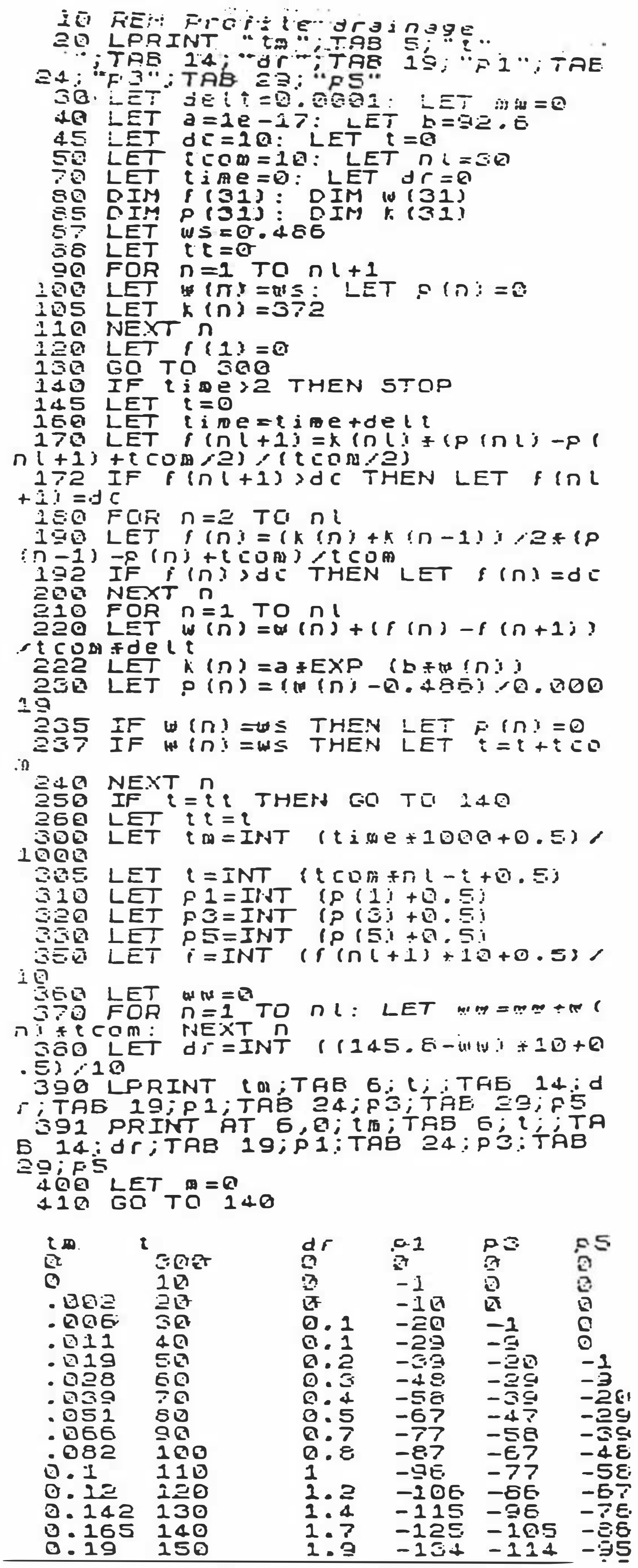
$$W = 145.8 - 9.5 \times 10^{-5} T^2, \qquad (D.6)$$

and, noting that the cumulative drainage from an initially saturated profile (R) equals 145.8 - W, we find

$$T = (R/9.5 \times 10^{-5})^{\frac{1}{2}}. \qquad (D.7)$$

Given the drainage rate, equation (D.7) allows the watertable depth to be found as a function of time.

The modelled decline in the watertable depth with transient unsaturated flow with $q = 10$ mm d^{-1} at the base of the profile is shown in Fig. D.2. Also shown is the predicted decline if instantaneous potential equilibrium is assumed to occur during drainage, obtained as described above. The time taken for the watertable to reach 200 mm depth (the 'safe grazing' depth), differs by only 0.04 days (1 hour). This is a negligible difference both in practical terms, and in terms of the uncertainties in the drainage times induced by other assumptions made in Chapter 7.



```
 10 REM Profile drainage
 20 LPRINT "tm";TAB 5;"t
 ";TAB 14;"dr";TAB 19;"p1";TAB
24;"p3";TAB 29;"p5"
 30 LET delt=0.0001: LET ww=0
 40 LET a=1e-17: LET b=92.6
 45 LET dc=10: LET t=0
 50 LET tcom=10: LET nl=30
 70 LET time=0: LET dr=0
 80 DIM f(31): DIM w(31)
 85 DIM p(31): DIM k(31)
 87 LET ws=0.486
 88 LET tt=0
 90 FOR n=1 TO nl+1
100 LET w(n)=ws: LET p(n)=0
105 LET k(n)=372
110 NEXT n
120 LET f(1)=0
130 GO TO 300
140 IF time>2 THEN STOP
145 LET t=0
160 LET time=time+delt
170 LET f(nl+1)=k(nl)*(p(nl)-p(
nl+1)+tcom/2)/(tcom/2)
172 IF f(nl+1)>dc THEN LET f(nl
+1)=dc
180 FOR n=2 TO nl
190 LET f(n)=(k(n)+k(n-1))/2*(p
(n-1)-p(n)+tcom)/tcom
192 IF f(n)>dc THEN LET f(n)=dc
200 NEXT n
210 FOR n=1 TO nl
220 LET w(n)=w(n)+(f(n)-f(n+1))
/tcom*delt
222 LET k(n)=a*EXP (b*w(n))
230 LET p(n)=(w(n)-0.486)/0.000
19
235 IF w(n)=ws THEN LET p(n)=0
237 IF w(n)=ws THEN LET t=t+tco
m
240 NEXT n
250 IF t=tt THEN GO TO 140
260 LET tt=t
300 LET tm=INT (time*1000+0.5)/
1000
305 LET t=INT (tcom*nl-t+0.5)
310 LET p1=INT (p(1)+0.5)
320 LET p3=INT (p(3)+0.5)
330 LET p5=INT (p(5)+0.5)
350 LET f=INT (f(nl+1)*10+0.5)/
10
360 LET ww=0
370 FOR n=1 TO nl: LET ww=ww+w(
n)*tcom: NEXT n
380 LET dr=INT ((145.8-ww)*10+0
.5)/10
390 LPRINT tm;TAB 6;t;;TAB 14;d
r;TAB 19;p1;TAB 24;p3;TAB 29;p5
391 PRINT AT 6,0;tm;TAB 6;t;;TA
B 14;dr;TAB 19;p1;TAB 24;p3;TAB
29;p5
400 LET m=0
410 GO TO 140
```

```
tm     t         dr    p1    p3    p5
0       300      0     0     0     0
0       10       0     -1    0     0
.002    20       0     -10   0     0
.006    30       0.1   -20   -1    0
.011    40       0.1   -29   -9    0
.019    50       0.2   -39   -20   -1
.028    60       0.3   -48   -29   -3
.039    70       0.4   -58   -39   -20
.051    80       0.5   -67   -47   -29
.066    90       0.7   -77   -58   -39
.082    100      0.8   -87   -67   -48
0.1     110      1     -96   -77   -58
0.12    120      1.2   -106  -86   -67
0.142   130      1.4   -115  -96   -78
0.165   140      1.7   -125  -105  -88
0.19    150      1.9   -134  -114  -95
```

Figure D.1 Program listing and sample output for transient drainage of a saturated soil profile .

Table D.1 Explanation of main symbols used in Fig. D.2

Symbol	Definition
delt	time step used (d)
dc	assumed drainage rate from profile (mm d^{-1})
tcom	segment depth used (mm)
nl	number of segments
ws	porosity
w(n)	volumetric water content in segment n
f(n)	flux density through top of segment n
p(n)	pressure potential in segment n
k(n)	hydraulic conductivity in segment n
tm	time (d)
t	watertable depth (mm)
dr	cumulative drainage from profile (mm)

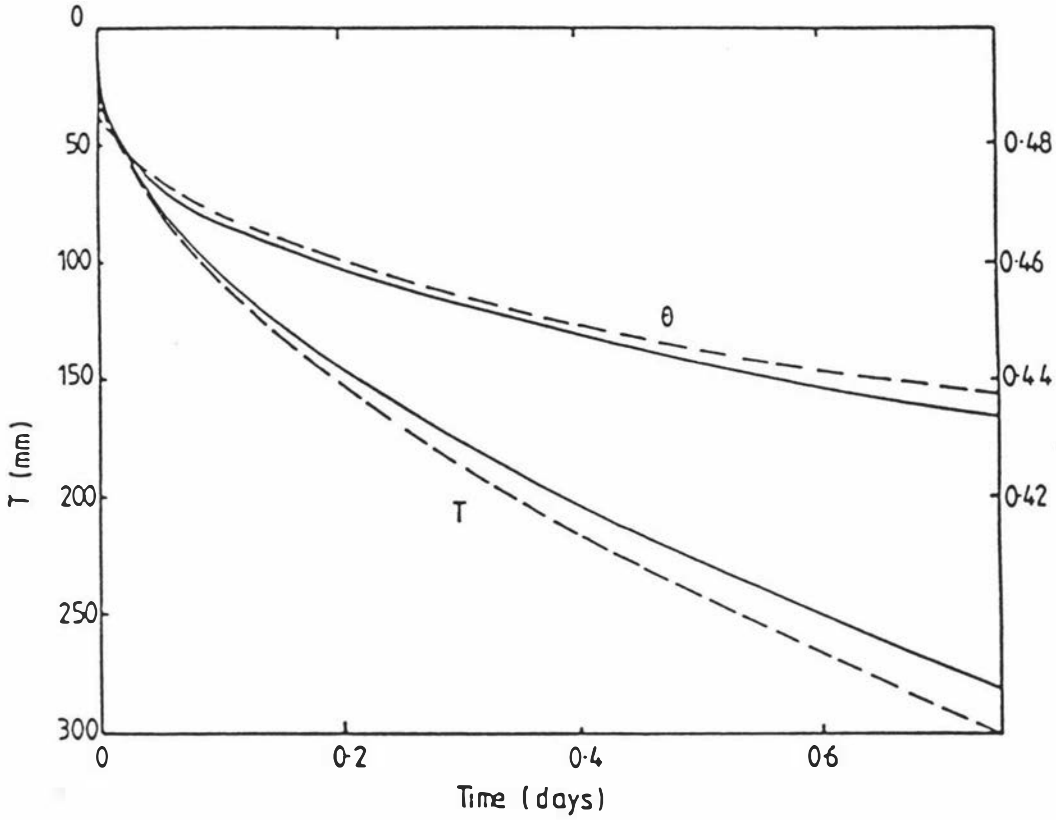


Figure D.2. Modelled watertable level (T) and volumetric water content (θ) at 5 mm depth when instantaneous matric potential equilibrium in the unsaturated soil is assumed (——) and when transient flow in the unsaturated zone is taken into account (– – –). The soil profile is assumed to be initially saturated and to have a vertical drainage flux density of 10 mm d^{-1}.

Appendix E: Program listing and sample output for model to predict the watertable level in a mole drained soil.

Figure E.1 Program listing of the model described in Chapter 7 for predicting watertable levels in a mole drained soil.

```
100    REM  MODEL  TO PREDICT THE  WATERTABLE LEVEL (WT) IN MOLE DRAINED SOIL
110    REM  A,B,C = quadratic coefficients
120    REM  T(N)    = depth to WT in segment N
130    REM  T       = time
140    REM  T1      = time increment
150    REM  T2      = WT midway between moles
160    REM  T3      = WT quater-way between moles
170    REM  T4      = WT mean between moles
180    REM  M       = print increment
190    REM  M1      = print counter
200    REM  H       = No. Days WT less than 200mm
210    REM  K(N)     = hydraulic conductivity in segment N
220    REM  X,Y,Z  = parameters in hydraulic conductivity equation
230    REM  R(N)     = runoff from segment N
240    REM  R       = daily runoff at mole
250    REM  R1      = runoff at mole
260    REM  Q(N)     = flow in segment N
270    REM  Q       = flow to mole
280    REM  Q1      = daily flow to mole
282    REM  T-QU    = depth to WT in segment N1/2 at end of day
284    REM  T-MID   = depth to WT in segment N1 at end of day
286    REM  T-MN    = average depth to WT at end of day
290    REM  D       = rainfall - evapotraspiration
300    REM  D1      = day
310    REM  V       = average WT
320    REM  W(N)     = water in segment N
330    REM  W       = width of segment
340    REM  N1      = number of segments
350    REM  N       = counter for N1
352    REM  I       =drainage coefficient
354    REM  P       =counter for time when flow in drain is maximum
360 PRINT "Day"; TAB( 6);"W"; TAB( 13);"T-QU"; TAB( 19);"T-MID"; TAB( 25);"T-MN"; TAB( 31);"ROFF";
                                            TAB( 36);"QOFF";TAB(43);"TLIM"
370 T1 = .001
375 P=0
380 M = 1000
385 I=10
390 H = 0
400 R = 0
410 Q = 0
420 D1 = 0
430 V = 328
440 D = 0
450 W = 166.67
460 T = 0
470 N1 =  INT (1000 / W + 0.5)
480 DIM T(21),Q(21),W(21),K(21),R(21)
490 FOR N = 1 TO N1
500    T(N) = 328
510    W(N) = 208.1
520    NEXT N
530 Q(0) = 0
540 R(0) = 0
550 GOTO 990
560 M1 = 0
570 READ D
580 Q1 = 0
590 R1 = 0
600 IF D > 200 THEN GOTO 1510
```

```
610 T = T + T1
620 FOR N = 1 TO N1
630     IF T(N) < 450 AND T(N) >   300 THEN  K(N)=37
640     IF T(N)= < 300 AND T(N) >  =  - 2 THEN  GOTO 1470
650     IF T(N) = 450 THEN K(N) = 0
660     GOTO 680
670     K(N) =( X + Y * (Z - T(N))) / (450 - T(N))
680     NEXT N
690 T(N1 + 1) = 450
700     REM  AS DISTANCE FROM SEGMENT N1 TO MOLE IS ONLY HALF WIDTH NEED DIFFERENT EXPRESION
710 Q(N1) = K(N1) * ((T(N1 + 1) - T(N1)) / W) * 2 * (450 - (T(N1) + T(N1 + 1)) / 2)
713 IF Q(N1)>I*1000 THEN P=P+T1
715 IF Q(N1)>I*1000 THEN Q(N1)=I*1000
720 FOR N = 1 TO N1 - 1
730     Q(N) = (K(N) + K(N + 1)) / 2 * (T(N + 1) - T(N)) / W * (450 - (T(N) + T(N + 1)) / 2)
740     NEXT N
750 Q1 = Q1 + (Q(N1) * T1 / 1000)
760 FOR N = 1 TO N1
770     W(N) = W(N) + ((Q(N - 1) - Q(N)) / W * T1) + D * T1 + R(N - 1)
780     R(N) = 0
790     IF W(N) > 222. 1 THEN  GOTO 1180
800     IF W(N) <  = 222. 1 AND W(N) >  = 220. 1 THEN  GOTO 1210
810     IF W(N) < 220. 1 AND W(N) >  = 217. 4 THEN  GOTO 1230
820     IF W(N) < 217. 4 AND W(N) >  = 212. 9 THEN  GOTO 1270
830     IF W(N) < 212. 9 AND W(N) >  = 206. 5 THEN  GOTO 1310
840     IF W(N) < 206. 5 AND W(N) >  = 199. 2 THEN  GOTO 1350
850     IF W(N) < 199. 2 THEN  GOTO 1390
860     T(N) = ( - B -  SQR (B * B - 4 * A * C)) / 2 / A
870     NEXT N
880 R1 = R1 + R(N1) / N1
890 LET M1 = M1 + 1
900 IF M1 < M THEN  GOTO 610
910 V = 0
920 FOR N = 1 TO N1
930     V = V + T(N)
940     NEXT N
950 V = V / N1
960 D1 =  INT (T * 100 + 0. 5) / 100
965 P1=  INT(P*100+0. 5)/100
970 R =  INT (R1 * 100 + 0. 5) / 100
980 Q =  INT (Q1 * 100 + 0. 5) / 100
990 T2 =  INT (T(1) + 0. 5)
1000 T3 =  INT (T(N1/2) + 0. 5)
1010 T4 =  INT (V + 0. 5)
1020 IF T4 <  = 200 THEN  LET H = H + 1
1030 PRINT D1; TAB( 6);D; TAB( 13);T3; TAB( 19);T2; TAB( 25);T4; TAB( 31);R; TAB( 36);Q;TAB(43);P1
1040 GOTO 560
1050 DATA  -1. 1, -1. 2, 1, 0, -0. 5, -1. 3, -1. 3
1180 R(N) = W(N) - 222. 1
1190 W(N) = 222. 1
1200 GOTO 1210
1210 T(N) = 220. 1 - W(N)
1220 GOTO 870
1230 A =  - 0. 00012
1240 B = 0
1250 C = (220. 1 - W(N))
1260 GOTO 860
1270 A =  - 9. 5E - 5
1280 B =  - 0. 0075
1290 C = (220. 7 - W(N))
```

```
1300 GOTO 860
1310 A =  - 8E - 5
1320 B =  - 0 015
1330 C = (221 6 - W(N))
1340 GOTO 860
1350 A =  - 2. 5E - 5
1360 B =  - 0. 0535
1370 C = (228. 3 - W(N))
1380 GOTO 860
1390 A =  - 1
81400 B = 450
1410 C = 0
1420 GOTO 860
1470 X = 5550
1480 Y = 372
1490 Z = 300
1500 GOTO 670
1510 PRINT "No.  of days Water Table is above 200mm = ",H
1520 END
```

```
Day   W       T-QU   T-MID  T-MN   ROFF  QOFF    TLIM
0     0       328    328    328    0     0       0
1     -1. 1   348    344    360    0     1. 21   0
2     -1. 2   370    363    382    0     . 36    0
3     1       361    353    372    0     . 31    0
4     0       366    358    377    0     . 34    0
5     -. 5    377    369    387    0     . 24    0
6     -1. 3   397    390    406    0     . 11    0
7     -1. 3   416    410    424    0     . 02    0
```

APPENDIX F:

COMPARISON OF MEASURED AND SIMULATED VALUES OF THE GRAVIMETRIC WATER CONTENT OF THE SURFACE SOIL AND THE WATERTABLE DEPTH AT POSITIONS ADJACENT TO THE MOLE AND MIDWAY BETWEEN MOLES

D.R. Scotter and D.J. Horne

The model was used to predict the gravimetric water content in the top 30 mm of the soil profile, and also the watertable depth midway between mole channels and 100 mm from a mole channel. The simulated values were then compared with the measured data presented in Chapter 3.

To calculate the volumetric water content (θ) in the top 30 mm of the soil profile from the pressure potential, the relationship discussed in Section 7.3 was used, namely,

$$\theta = aP + f. \qquad (F.1)$$

The physical properties for the top 150 mm of soil given in Table 7.2 are not necessarily applicable to the top 30 mm. Mean values of 0.89 Mg m^{-3} and 0.14 for the bulk density and the air-filled porosity at a matric potential of -5 kPa were found from cores taken at the site on 30/7/1983 (W.C. Climo, pers. comm.). Assuming a particle density of 2.6 Mg m^{-3}, this gives values of 0.00028 mm^{-1} and 0.66 for a and f respectively, and these were the values used in equation F.1 in the simulation.

The value of the pressure potential was estimated as the height above the watertable so that for the mid-point of the 30 mm surface layer of soil

$$P = 15 - T \quad (mm). \qquad (F.2)$$

Substituting equation (F.2) and the appropriate values for a and f, into equation (F.1) yields,

$$\theta \;=\; 0.00028\;(15 - T) \;+\; 0.66\;. \qquad (F.3)$$

As θ and the gravimetric water content (w) are related by

$$\theta \;=\; (p_b/p_w)\,w \qquad (F.4)$$

where p_w is the density of water, we find

$$w \;=\; -\,0.000315\;T \;+\; 0.746\;. \qquad (F.5)$$

By inserting the simulated watertable depth for each day (Chapter 7) into equation (F.5) it was possible to predict daily values for the gravimetric water content of the top 30 mm of the soil profile. A comparison is made in Fig. F.1 between these simulated water content values and the measured values.

Because the bulk density of the top 30 mm, and therefore, the porosity probably changed following grazing and pugging it is not suprising that the model cannot accurately predict the absolute values of the gravimetric water content of the surface soil. However, the simulated values parallel very closely the trends in the measured data and the predicted differences between the values for drained and undrained plots is approximately equal to the measured differences.

The model described in Chapter 7 was used to predict the watertable depth at positions midway between mole channels and adjacent to the mole. Chapter 7 described how the numerical analysis partioned the drained soil into six compartments and computed the depth to the watertable in each compartment. At the end of the day, the watertable depth in all compartments were averaged to find the watertable level for that day. However, in Figs. F.2 and F.3 are shown the predicted watertable depths in compartment 1, (corresponding to the mid-mole position) and compartment 6 (corresponding to the adjacent to the mole position). Also shown are

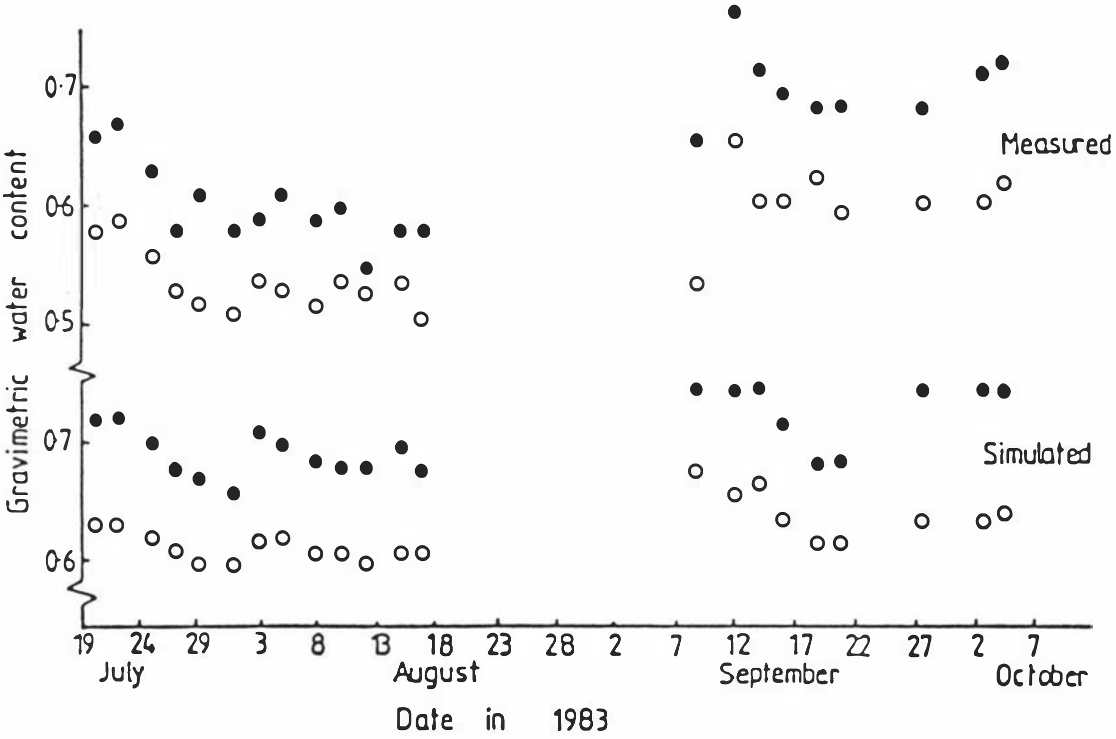


Figure F.1 Comparison between simulated and measured gravimetric water content of the top 30 mm of the drained (○) and undrained (●) soil profiles

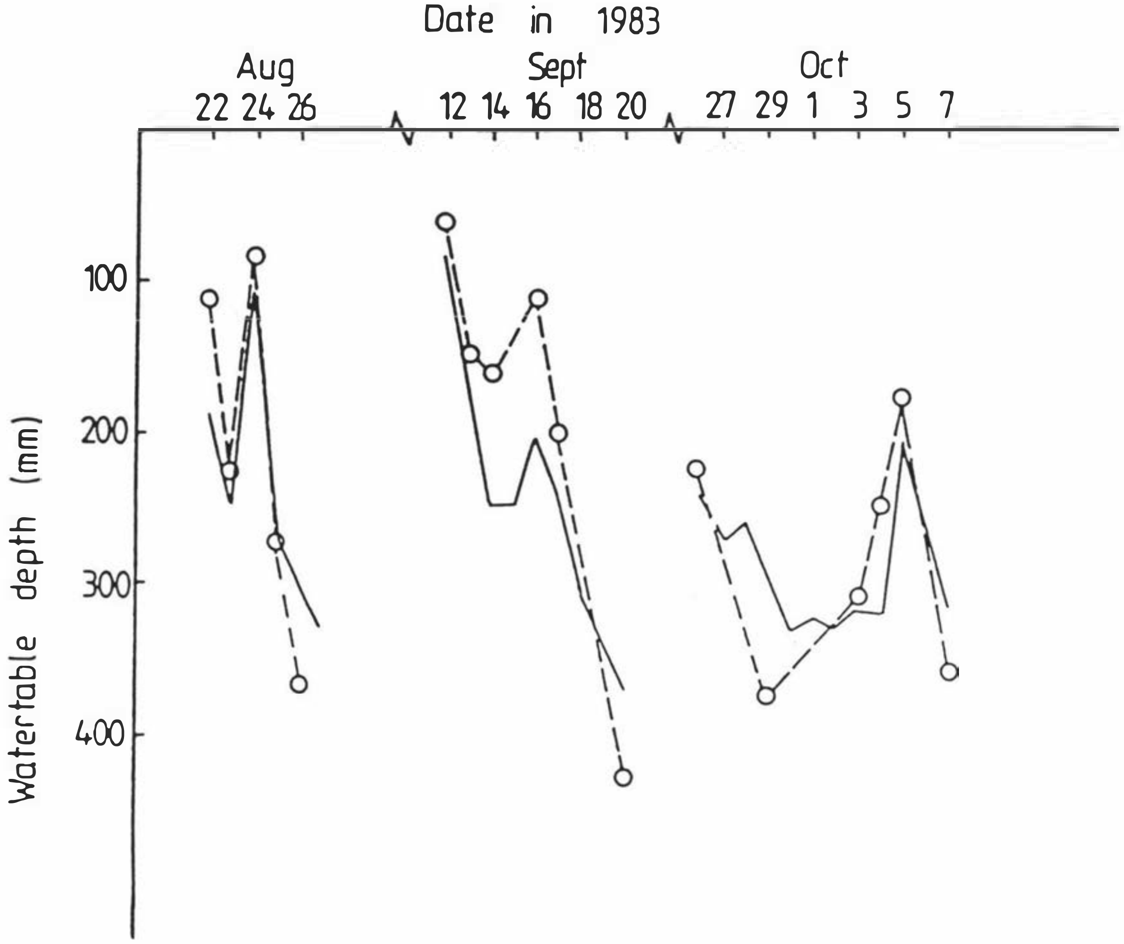


Figure F.2 Comparison between simulated (——) and measured (O--O) watertable depths at a position midway between mole channels .

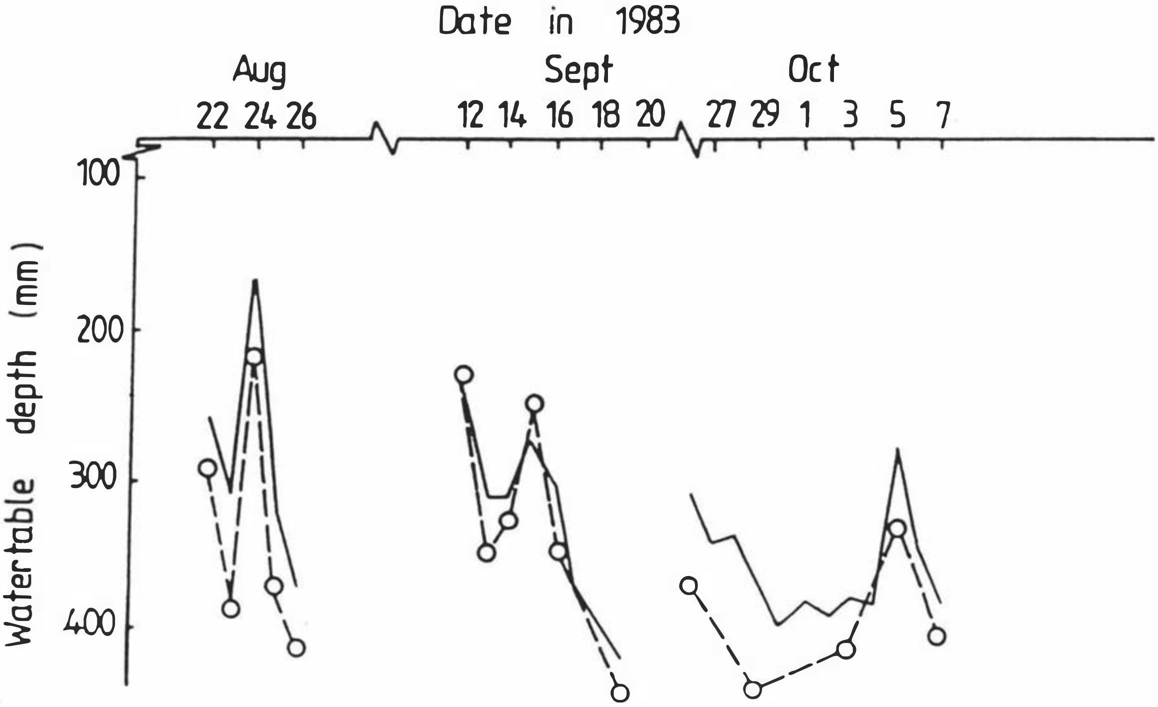


Figure F.3 Comparison between simulated (———) and measure (○--○) watertable depths at a position adjacent to the mole channel .

the measured data from Fig. 3.8. Agreement between simulated and measured values is good, especially when the size of the standard deviation for the measured values is considered. Such good agreement between modelled and measured data indicates that, as assumed in the model, there is no major impedance to the flow of water into the mole itself despite the consolidating effect the mole blade must have had on the channel wall.

In conclusion, it is noted that the model was reasonably accurate not only in its prediction of the mean watertable level (Chapter 7), but also in its prediction of the shape of the watertable and of the differences in surface soil water content.

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