Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
SOME CONSEQUENCES OF MOLE DRAINING A
YELLOW-GREY EARTH UNDER PASTURE

A thesis presented in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy in Soil Science
at Massey University

David John Horne
1985
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.

Water table 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 occurring 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 water table 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.
ACKNOWLEDGEMENTS

I gratefully acknowledge the assistance of the following people:

Professor J.K. Syers for supervision and encouragement during this study.

Mr. R.W. Tillman for supervision, guidance and direction, particularly with the experimental parts of the study.

Dr. D.R. Scott for supervision, guidance and direction, particularly with those aspects related to soil physics and computer modelling.

Mr. I. Furse for invaluable technical assistance throughout this study. Other members of the Department of Soil Science, particularly Messrs Martin Lewis, Keith McAuliffe and Warren Climo.

Mr. E. Roberts of the Department of Agronomy for instruction in determining botanical composition by point analysis.

The National Water and Soil Conservation Authority for funding this project.

The supervisor and staff of Keeble farm for their co-operation and assistance.

The Drainage Extension Service of Massey University for designing and installing the drainage system.

Dianne Syers for typing this thesis.

Massey University for the Bank of New Zealand Postgraduate Bursary, Farmers Union Scholarship, Helen E. Akers Scholarship, Johannes August Anderson Scholarship and the Massey Graduate Award.

Most importantly, my family, especially my parents.
TABLE OF CONTENTS

ABSTRACT .................................................. ii
ACKNOWLEDGEMENTS ....................................... vi
TABLE OF CONTENTS ....................................... vii
LIST OF FIGURES ........................................ xiv
LIST OF TABLES ........................................... xxiii

CHAPTER 1
GENERAL INTRODUCTION .................................. 1
1.1 The Need for Research into the Effects of Drainage .... 2
1.2 Claimed Benefits of Drainage ....................... 3
1.3 An Overview of Drainage Techniques ................. 4
1.4 Objectives of this Study ............................ 6

CHAPTER 2
GENERAL DESCRIPTION OF THE KEEBLE FARM DRAINAGE EXPERIMENT ... 8
2.1 Introduction ........................................ 9
2.2 The Experimental Site ................................ 9
2.3 Plot Layout and Drainage Treatments ............... 11
2.4 Parameters Measured ................................ 13

CHAPTER 3
THE EFFECT OF MOLE DRAINAGE ON SOIL WATER ............ 15
3.1 Introduction ...................................... 16
3.2 Materials and Methods ............................ 19
   3.2.1 Watertable levels .......................... 19
   3.2.2 Water content of the soil .................. 19
### Chapter 3

**3.2.3 Drainage from the plots**

**3.2.4 Statistical analysis**

**3.3 Results and Discussion**

**3.3.1 Effect of drainage on the watertable level**

- **3.3.1.1** 1982 - a dry year
- **3.3.1.2** 1983 - an average year

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

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

**3.3.4 Effect of drainage on soil water content**

- **3.3.4.1** 1982 - a dry year
- **3.3.4.2** 1983 - an average year

**3.4 Conclusions**

### Chapter 4

**4.1 Introduction**

**4.2 Materials and Methods**

- **4.2.1 Pasture production**
- **4.2.2 Pasture utilisation**
- **4.2.3 Dung return to the plots**
- **4.2.4 Statistical analysis**

**4.3 Results**

**4.3.1 Effect of drainage on pasture utilisation in winter**

- **4.3.1.1** 1982 - a dry winter
- **4.3.1.2** 1983 - an average winter
- **4.3.1.3** 1984 - an average winter
4.3.2 **Effect of drainage on pasture utilisation in spring** .......................... 59
   4.3.2.1 1983 - an average spring ........................................... 59
   4.3.2.2 Differences in camping behaviour ............................... 67

4.3.3 **Effect of drainage on pasture production** ............................. 65
   4.3.3.1 1981 - background year ............................................. 65
   4.3.3.2 1982 - a dry year .................................................. 65
   4.3.3.3 1983 - an average year ............................................. 65

4.4 Discussion ................................................................. 69

4.5 Conclusions ................................................................. 74

---

**CHAPTER 5**

THE EFFECTS OF DRAINAGE ON THE BOTANICAL AND CHEMICAL
COMPOSITION OF PASTURE AND ON THE PLANT ROOT SYSTEM ................. 75

5.1 Introduction ................................................................. 76

5.2 Materials and Methods .................................................. 79
   5.2.1 Botanical composition .................................................. 79
   5.2.2 Chemical composition of pasture ...................................... 80
   5.2.3 Soil nutrient status ..................................................... 80
   5.2.4 Relative root activity .................................................. 82
   5.2.5 Statistical analysis ..................................................... 83

5.3 Results ....................................................................... 84
   5.3.1 **Effect of drainage on botanical composition** .................. 84
      5.3.1.1 1982 - a dry year ................................................. 84
      5.3.1.2 1983 - an average year ......................................... 84
   5.3.2 **Effect of drainage on the chemical composition of pasture** 89
      5.3.2.1 1982 - a dry year ................................................. 89
      5.3.2.2 1983 - an average year ......................................... 89
5.3.3 Effect of drainage on soil nutrient status .......................... 92
5.3.3.1 1982 - a dry year .................................................. 92
5.3.3.2 1983 - an average year ........................................... 92
5.3.4 Effect of drainage on the plant root system ......................... 94
5.3.4.1 Relative root activity during winter ............................... 94
5.3.4.2 Relative root activity during spring .............................. 94

5.4 Discussion ........................................................................ 99
5.5 Conclusions ....................................................................... 107

CHAPTER 6
THE EFFECT OF DRAINAGE ON SOIL TEMPERATURE AND AERATION .... 108
6.1 Introduction ...................................................................... 109
6.2 Materials and Methods ...................................................... 111
6.3 Results and Discussion ...................................................... 111
6.3.1 Effect of drainage on soil temperature .............................. 111
6.3.1.1 Soil temperature data ................................................ 111
6.3.1.2 Discussion of soil temperature and drainage ................. 113
6.3.1.3 Simulations of soil temperature .................................. 115
6.3.2 Effect of drainage on soil aeration ................................... 122
6.3.2.1 Soil aeration in an undrained soil .............................. 122
6.3.2.2 Direct effects of soil aeration on pasture growth ........... 123
6.3.2.3 Indirect effects of soil aeration on pasture growth .......... 124
6.4 Conclusions ..................................................................... 125

CHAPTER 7
MODELLING THE EFFECT OF MOLE DRAINAGE ON WATERTABLE
LEVELS AND THE NUMBER OF UNSAFE GRAZING DAYS .................. 127
7.1 Introduction ...................................................................... 128
7.2 Overview of Soil Water Statics and Dynamics ....................... 130
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 ($\theta$)

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

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

7.4 Running the Model for an Undrained Soil

7.4.1 1983 - an average year

7.4.2 1982 - a dry year

7.4.3 1976 - a wet year

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

7.5.2 Effect of lateral flow on the watertable level

7.5.3 Parameterisation of the model

7.6 Running the Model for a Pipe-Mole Drained Soil

7.6.1 1983 - an average year

7.6.2 1982 - a dry year

7.6.3 1976 - a wet year

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

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

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

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

7.9 Conclusions
## CHAPTER 8

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

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Introduction</td>
<td>162</td>
</tr>
<tr>
<td>8.2 Results and Discussion</td>
<td>163</td>
</tr>
<tr>
<td>8.2.1 Profile of watertable decline</td>
<td>164</td>
</tr>
<tr>
<td>8.2.2 Effect of varying the hydraulic conductivity ($K_A$, $K_B$)</td>
<td>164</td>
</tr>
<tr>
<td>8.2.3 Effect of varying the mole spacing ($s$)</td>
<td>167</td>
</tr>
<tr>
<td>8.2.4 Effect of varying the evapotranspiration ($E$)</td>
<td>171</td>
</tr>
<tr>
<td>8.2.5 Effect of varying the drainage coefficient ($I$)</td>
<td>175</td>
</tr>
<tr>
<td>8.2.6 Effect of varying soil water retentivity ($a_i$)</td>
<td>179</td>
</tr>
<tr>
<td>8.2.7 Comparison of the volume of water leaving the soil as runoff ($S$) with that leaving as drainage ($L$)</td>
<td>182</td>
</tr>
<tr>
<td>8.3 Conclusions</td>
<td>186</td>
</tr>
</tbody>
</table>

## CHAPTER 9

**AN OVERVIEW**

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>187</td>
</tr>
</tbody>
</table>

## APPENDIX A

**Soil Profile Description**

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>194</td>
</tr>
</tbody>
</table>

## APPENDIX B

**Chemical Composition of Grass and Clover Sampled Between 20 October 1982 and 11 April 1983**

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>196</td>
</tr>
</tbody>
</table>

## APPENDIX C

**Thermal Properties of Drained and Undrained Soil**

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>197</td>
</tr>
</tbody>
</table>
C.1 Introduction .................................................. 197
C.2 Materials and Methods ................................. 197
C.3 Results and Discussion ................................. 199

APPENDIX D

Simulation of the Decline of the Watertable with
Transient Flow in the Unsaturated Zone .................. 203

APPENDIX E

Program Listing and Sample Output for Model to Predict
the Watertable Level in a Mole Drained Soil .. 208

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 .... 211

BIBLIOGRAPHY .................................................. 217
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Longterm average rainfall and Penman potential evaporation for Palmerston North</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Layout of drainage research area showing Plots 1 to 9</td>
<td>12</td>
</tr>
<tr>
<td>3.1</td>
<td>Diagram showing the location of groundwater observation wells (O) relative to mole channels (—), the elevated portions of the undrained Plots 3 and 7 (///), neutron moisture meter access tubes (●) and weirs (□).</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>View of V-notch weir and Stevens recorder</td>
<td>22</td>
</tr>
<tr>
<td>3.3</td>
<td>Rainfall and watertable levels as measured for pipe-mole (O--O), 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.</td>
<td>23</td>
</tr>
<tr>
<td>3.4</td>
<td>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.</td>
<td>25</td>
</tr>
<tr>
<td>3.5</td>
<td>Hydrographs showing similarity in performance of pipe-mole (— —) and mole-mole (——) treatments.</td>
<td>28</td>
</tr>
<tr>
<td>3.6</td>
<td>Decay curves following peak flow for pipe-mole (O--O) and mole-mole (□—□) plots</td>
<td>29</td>
</tr>
<tr>
<td>3.7</td>
<td>Comparison of watertable levels adjacent to the mole (●—●) with levels mid mole (O--O). Mean values and standard deviations shown are for the tubes on all the drained plots.</td>
<td>34</td>
</tr>
</tbody>
</table>
### Figure Page

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 .......................................................... 37

3.9 Gravimetric water content of top 30 mm of pipe-mole (O—O), mole-mole (□—□) and undrained (●—●) profile in 1982. Least significant difference (LSD) at the 1% and 5% level .......................................................... 38

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 $P \leq 0.05$ .......................................................... 39

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 1% and 5% level .......................................................... 41

3.12 Volumetric water content of pipe-mole (O—O) 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 $P \leq 0.05$ .......................................................... 43

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 .......................................................... 53

4.2 Plates illustrating difference in pasture utilisation between drained (Plot 8) and undrained (Plot 5) plots after the July, 1983 grazing .......................................................... 54
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.

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

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.

4.6 Pasture growth rates in 1981 for pipe-mole (O--O), 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.

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.
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.

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.

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

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.

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

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

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 $P \leq 0.05$. Mean values followed by different upper case letters are significantly different at $P \leq 0.01$. 
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 $P \leq 0.01$.

5.7 Volumetric water content of pipe-mole ($\bigcirc--\bigcirc$) and undrained ($\bullet--\bullet$) 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 $P \leq 0.05$.

5.8 Water table depths and daily maximum ($\bigcirc$, $\bigcirc$), mean ($\bullet$, $\bigcirc$) and minimum ($\blacktriangle$, $\blacktriangle$) 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 water-table was deeper than 450 mm it was assigned a value of 450 mm.

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

5.10 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 ($\bullet$).

5.11 Simulated diurnal soil temperatures at four depths in drained (-----) and undrained (-----) soil.
7.1 Equivalent depth of water (W) in the top 450 mm of the soil profile as a function of watertable depth (T) ........................................... 137

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 ........................................... 141

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<sub>c</sub> (mm<sup>3</sup> d<sup>-1</sup>) is the rate at which water flows out of compartment c, Q<sub>c-1</sub> is the rate at which water flows into compartment c and Q<sub>0</sub> 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<sub>f</sub> is the flow to the mole from the final compartment (f). R<sub>c-1</sub> (mm<sup>3</sup> d<sup>-1</sup>) is the rate of surface runoff onto compartment c and R<sub>c</sub> is the rate of surface runoff off compartment c. R<sub>f</sub> is the surface runoff from the final compartment (f). D is the daily rainfall minus evapotranspiration ........................................... 146

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<sub>A</sub> = 372 mm d<sup>-1</sup> and K<sub>B</sub> = 37 mm d<sup>-1</sup> and the values of Scotter et al. (1979a) with measured rates of decline (---). Simulations were carried out with 0 mm d<sup>-1</sup> (---) and 1 mm d<sup>-1</sup> (----) evapotranspiration ........................................... 151

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 ........................................... 153
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 .......................... 156

Figure 7.7 Number of unsafe grazing days on drained and undrained soil in the winter-spring period of 1982, 1983 and 1976 .......................... 159

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 .......................... 165

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 .......................... 166

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 .......................... 168

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 .......................... 170

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 .......................... 172
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.

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.

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.

8.9 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.

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.

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.

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.
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 (○) ....... 200

D.1 Program listing and sample output for transient drainage of a saturated soil profile ......... 205

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 ............... 207

E.1 Program listing of the model described in Chapter 7 for predicting watertable levels in a mole drained soil ................. 208

F.1 Comparison between simulated and measured gravimetric water content of the top 30 mm of the drained (○) and undrained (●) soil profiles ........ 213

F.2 Comparison between simulated (——) and measured (○--○) watertable depths at a position midway between mole channels ................. 214

F.3 Comparison between simulated (——) and measured (○--○) watertable depths at a position adjacent to the mole channel ................. 215
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Response times for the pipe-mole and mole-mole systems in 1983 (i.e. the times flow began after rainfall and the times flow peaked)</td>
<td>30</td>
</tr>
<tr>
<td>3.2</td>
<td>Volume of water ($m^3$) that flowed through the weirs during the first 12 hours after the commencement of flow</td>
<td>32</td>
</tr>
<tr>
<td>4.1</td>
<td>Pasture utilised during mob grazing in July, 1983. Mean values for a particular measurement technique followed by a different letter are significantly different at $P \leq 0.01$</td>
<td>55</td>
</tr>
<tr>
<td>4.2</td>
<td>Relationship between pasture utilisation, pugging and depth to the water table observed in July, 1983. Mean values of a parameter followed by a different letter are significantly different at $P \leq 0.01$</td>
<td>56</td>
</tr>
<tr>
<td>4.3</td>
<td>Pasture utilised during mob grazing in July, 1984 measured using the pasture meter</td>
<td>58</td>
</tr>
<tr>
<td>4.4</td>
<td>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 $P \leq 0.01$</td>
<td>64</td>
</tr>
<tr>
<td>5.1</td>
<td>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 $P \leq 0.05$</td>
<td>86</td>
</tr>
</tbody>
</table>
Table

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 Clover and weed content of sward (expressed as a percentage)</td>
<td>88</td>
</tr>
<tr>
<td>measured during spring and early summer of 1983/1984 by dissection.</td>
<td></td>
</tr>
<tr>
<td>Mean values of a category for a harvest followed by a different letter</td>
<td></td>
</tr>
<tr>
<td>are significantly different at $P \leq 0.05$.</td>
<td></td>
</tr>
<tr>
<td>5.3 Pasture composition (expressed as a percentage)</td>
<td>90</td>
</tr>
<tr>
<td>for drained and wet areas of undrained plots measured by the point</td>
<td></td>
</tr>
<tr>
<td>analysis technique on the 2 April, 1984. Mean values for a category</td>
<td></td>
</tr>
<tr>
<td>followed by a different letter are significantly different at $P \leq</td>
<td></td>
</tr>
<tr>
<td>0.05.</td>
<td></td>
</tr>
<tr>
<td>5.4 Soil test data obtained during the September and December isotope</td>
<td>97</td>
</tr>
<tr>
<td>trials (1983). Mean values at a particular depth for a nutrient</td>
<td></td>
</tr>
<tr>
<td>followed by a different letter are significantly different at $P \leq</td>
<td></td>
</tr>
<tr>
<td>0.05.</td>
<td></td>
</tr>
<tr>
<td>7.1 Soil water data for the four layers of Tokomaru silt loam</td>
<td>135</td>
</tr>
<tr>
<td>under consideration, along with the value of the coefficient $a_1$</td>
<td></td>
</tr>
<tr>
<td>defined by equation (7.6) for each layer.</td>
<td></td>
</tr>
<tr>
<td>7.2 Coefficients for use in equation (7.13)</td>
<td>136</td>
</tr>
<tr>
<td>along with range of W for which they apply.</td>
<td></td>
</tr>
<tr>
<td>A.1 Profile description of Tokomaru silt loam in Dairy Farm No. 4,</td>
<td>194</td>
</tr>
<tr>
<td>Massey University, Palmerston North (Pollok, 1975).</td>
<td></td>
</tr>
<tr>
<td>B.1 Percentage N, P and S in grass and clover for the spring - summer</td>
<td>196</td>
</tr>
<tr>
<td>D.1 Explanation of main symbols used in Fig. D.2</td>
<td>206</td>
</tr>
</tbody>
</table>