

Cranfield University

School of Applied Sciences
National Soils Resources Institute

Doctor of Philosophy

Academic year 2006 - 2007

Nicola J. Baggaley

**Modelling the drivers of soil moisture in the
landscape in order to apply the STAMINA
model at a regional level**

Supervised by Dr. Thomas Mayr

January 2007

© Cranfield University, 2007. All rights reserved. No part of this publication may be reproduced without the written permission of the copyright holder.

This thesis is submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

ProQuest Number: 10820970

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10820970

Published by ProQuest LLC (2018). Copyright of the Dissertation is held by Cranfield University.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

Abstract

The STAMINA (Stability And MitigationN of Arable systems in hilly landscapes) model is a new crop yield model than takes into account the impact of terrain on crop growth. The ability to model yield variations as a function of terrain can help policy makers plan for potential changes in climate. In its original form the STAMINA model is too complex to be run at a regional extent. The literature pointed to the key drivers of crop growth being linked to water availability in the landscape. The research was therefore split into two sections.

The first section outlines the investigation of soil moisture in the landscape. Two field experiments were undertaken. The first measured surface soil moisture at over 100 locations, using a Delta-T ThetaProbe on eight occasions in three different fields. The results from regression models showed that up to 80% of the variation in surface soil moisture can be explained using 1:10,000 taxonomic soil units. Radiation and wetness indices combined explained a maximum of 41% of the variation. These variables also explained significant additional variation when combined with 1:25,000 soil units. The second experiment measured soil moisture at six depths from 100 mm to 1 m at 38 locations in two fields using a Delta-T profile probe. Regression models showed that 1:10,000 taxonomic soil units combined with depth explain up to 67% of the variance in soil moisture. These results highlight the importance of the drainage characteristics of the soil profile in determining soil moisture content.

The second section focuses on the development of an index approach to apply the STAMINA model at a regional extent. This method and STAMINA version 1.8 were tested on three representative catchments in a 10 km² area of Bedfordshire. They succeeded in highlighting similar areas of the landscape that are at risk from low yields. Grid size analysis suggested that a grid size of 100 m was sufficient for running the index based version of the STAMINA model. This still maintained an accurate representation of the topographic features that control the modelled yield variability. Further investigation into the soil hydrology module in STAMINA version 1.8 suggested that predicted yield was very sensitive to a change in the way soil water drainage was modelled, in particular the potential for a soil to recharge over the winter months.

Acknowledgements

Firstly I would like to thank my supervisor Dr Thomas Mayr for his comments and guidance throughout the last three years and for the opportunity he gave me to work in Bari. I would also like to thank Professor Sue White and Tim Brewer for their helpful suggestions.

I would also like to thank the many members of what was NSRI for their thoughtful suggestions and practical help. In particular Pat Bellamy for her help with the statistics used, Rodney Burton for mapping the field sites and for all he taught me about soils in the landscape, Ian Bradley for asking the right questions and John Hollis for providing the data and background to the lysimeter experiments. Thanks to the guys on our computer help desk for letting me hijack PCs for several months when I was trying to run the STAMINA model. Thanks to all those who have helped me with my field work, Jim, Mark, Julia, Ian and Thomas. I would especially like to thank Helen for her patience and making Fridays in the field a welcome break from the office even when attempting to find access tubes in a field of Oil Seed Rape. I would also like to thank Matt for his work on the STAMINA project before I started.

Thanks to the members of the STAMINA project team. Patrizia Trevisiol, Rossana Ferrera and Mario Ludato for their patient help in getting the model to run on my computer and always being on hand to answer my questions. Thanks to Dr Gianfranco Rana and Dr Dominico Ventrella for their helpful advice and giving me the opportunity to work with them in Bari. I would also like to thank Dr. Thorsten Behrens for allowing us to use the CAS (Computer Aided Sampling) software. I would like to thank Guy Kiddy, Peter Allen and Paul Walsh for letting me carry out soil moisture sampling in their fields. I would like to thank the Bomford Trust (Institution of Agricultural Engineers) for assisting with my living expenses in my final year.

Special thanks to Julia, Helen and Liz, friends and family at home and abroad for your encouragement and friendship and putting up with me at my most stressed. A huge thank you to my Church family at Ampthill Baptist Church, for their care, concern and practical help. The last three years would not have been possible without you. Finally I would like to thank my Mum and Dad, without their loving support I would not be where I am now.

**“I lift up my eyes to the hills,
Where does my help come from?
My help comes from the LORD,
The maker of heaven and earth.”**

Psalm 121 v1-2

(Holy Bible, New International Version)

Contents

Abstract	I
Acknowledgements.....	II
Contents	IV
List of figures	IX
List of tables	XV
List of abbreviations	XVI
1 Introduction.....	1
1.1 Agriculture and climate change.....	1
1.2 Impact of terrain on agriculture.....	2
1.3 STAMINA project – context.....	3
1.3.1 STAMINA model – overview	5
1.3.2 The physically based approach to the STAMINA model	6
1.3.3 The problem.....	9
1.3.4 The approach adopted	10
1.4 Aim and objectives of this thesis	12
1.4.1 Aim	12
1.4.2 Objectives	12
1.5 Development of this thesis.....	13
2 Literature review	16
2.1 Soil moisture – an introduction.....	16
2.2 Effects of soil moisture.....	17
2.3 Processes which control soil moisture in the landscape	18
2.3.1 Temporal variation of soil moisture.....	19
2.4 Water and plant growth.....	22
2.5 Controls on soil moisture	23
2.6 Modelling soil moisture variation	26
2.7 Indices for distributed soil moisture modelling	26
2.7.1 Terrain based wetness Indices.....	26
2.7.2 Terrain based radiation indices	30
2.7.3 Terrain base temperature indices.....	34

2.8	Discussion of the use of terrain based indicators.....	35
2.9	Software packages for calculating terrain indices	37
2.9.1	TAPES-G	38
2.9.2	DYNWET-G.....	39
2.9.3	SRAD.....	40
2.10	Grid size and soil scale	41
2.11	Approaches to modelling at a regional level	42
2.12	Selecting representative areas in the landscape	45
2.13	Summary.....	47
3	Materials and Methods	49
3.1	Introduction	49
3.2	Site description and data	49
3.2.1	Study area.....	49
3.2.2	Field sites.....	52
3.3	Data available for analysis	57
3.3.1	Digital Terrain Model.....	57
3.3.2	Soil Maps and data.....	57
3.3.3	Weather data.....	59
3.4	Measurement of soil moisture	60
3.4.1	Surface soil moisture surveys.....	62
3.4.2	Soil moisture profile probe measurements	64
3.5	DTM calculations	67
3.5.1	Introduction	67
3.5.2	Calculation of critical upslope area.....	68
3.5.3	Calculation of drainage density.....	70
3.5.4	The settings for use of TAPES-G/ DYNWET-G/SRAD	70
3.6	Method for the lysimeter experiments	71
4	Surface soil moisture surveys.....	72
4.1	Introduction	72
4.2	Rainfall.....	72
4.3	Surface soil moisture analysis.....	74
4.4	Temporal variation	78
4.4.1	Stone Hill - 2004.....	78
4.4.2	Church Meadow - 2005	78

4.4.3	<i>Mox Farm - 2005</i>	78
4.5	Soil moisture variation with respect to soils	80
4.5.1	<i>Stone Hill- 2004</i>	80
4.5.2	<i>Church Meadow-2005</i>	81
4.5.3	<i>Mox Farm - 2005</i>	81
4.6	Soil moisture variation with respect to topography.....	83
4.6.1	<i>Stone Hill-2004</i>	84
4.6.2	<i>Church Meadow-2005</i>	85
4.6.3	<i>Mox Farm-2005</i>	85
4.7	Soil moisture with respect to terrain and soils combined.....	86
4.7.1	<i>Stone Hill-2004</i>	86
4.7.2	<i>Church Meadow-2005</i>	87
4.7.3	<i>Mox Farm-2005</i>	87
4.8	Discussion.....	88
4.8.1	<i>Local soils and geology</i>	88
4.8.2	<i>Controls on surface soil moisture</i>	89
4.9	Major Results	91
4.9.1	<i>Implications for the STAMINA model</i>	92
5	Soil moisture access tube results	93
5.1	Introduction	93
5.2	Access tubes.....	93
5.2.1	<i>Measurement errors</i>	95
5.2.2	<i>Discussion</i>	97
5.3	Weather conditions	98
5.4	Soil moisture analysis	100
5.5	Results	101
5.5.1	<i>Stone Hill 2003</i>	101
5.5.2	<i>Stone Hill 2004</i>	108
5.5.3	<i>Stone Hill discussion</i>	114
5.5.4	<i>Church Meadow 2003</i>	114
5.6	Discussion.....	120
5.7	Major results.....	122
5.8	Implications for the STAMINA model	122

6	Regional application of the STAMINA model.....	124
6.1	Approach.....	124
6.2	Index based method	124
6.3	Selecting representative catchments.....	126
6.3.1	<i>Method.....</i>	<i>127</i>
6.3.2	<i>Selection of representative catchments in the study area</i>	<i>130</i>
6.4	STAMINA runs for representative areas	135
6.4.1	<i>Results for running the model for representative areas</i>	<i>135</i>
6.5	Regression approach.....	138
6.5.1	<i>Results of the regression</i>	<i>138</i>
6.6	Drivers in the model.....	141
6.7	Discussion.....	142
7	Sensitivity Analysis to drainage function	146
7.1	Drainage functions used in the STAMINA model	146
7.2	The Lysimeter Study	148
7.2.1	<i>Method.....</i>	<i>148</i>
7.2.2	<i>Results.....</i>	<i>148</i>
7.3	Analysis of predicted yields from representative areas	152
7.3.1	<i>Method.....</i>	<i>152</i>
7.3.2	<i>Results.....</i>	<i>152</i>
7.4	Discussion.....	154
7.5	Major results.....	159
8	Sensitivity analysis to grid size and soil scale.....	160
8.1	Effect of grid size on indices at a regional level	160
8.2	Effect of grid size of and input soil resolution on yield variability	164
8.3	Discussion.....	167
8.4	Major results.....	169
9	Conclusions	170
9.1	Introduction	170
9.2	Soil moisture variation	172
9.3	The STAMINA model	173
9.4	Conclusion and recommendations	176

10	References	178
	Appendix I	193
	Appendix II.....	195
	Appendix III.....	197
	Appendix IV	198
	Appendix V	201
	Appendix VI	202
	Appendix VI	220

List of figures

Figure 1-1 The principles of the Mico-Meteorological part of the STAMINA model. Data recorded at a the lowest point in a catchment are distributed in the catchment based on topographic variables	6
Figure 1-2 The topographic parameters required for defining a cell in the landscape for input into the physically based STAMINA model	8
Figure 1-3 The definition of the "shape" of the landscape in the STAMINA model as based on the percentage of land in the upper and lower parts of the hillslope that are convex or concave (In profile curvature	9
Figure 1-4 The principle of applying the STAMINA model at a regional level based on data measured at a regional meteorological station.....	10
Figure 1-5 The two approaches to the application of the STAMINA model, showing how terrain variables are input into a micrometeorological module (Index based or Energy balance) which links to a soil hydrology module and then into the crop growth module. The concept was then to improve the index based approach based on a regression estimator.....	11
Figure 2-1 The factors in the landscape that drive soil moisture and can be used to predict it (Left) and the phenomena that it influences (Right).....	16
Figure 2-2 The processes which drive soil moisture in the landscape (Adapted from Rowell, 1994)	19
Figure 2-3 Factors that influence the hydrological response of a catchment (After Hawley <i>et al.</i> , 1993)	26
Figure 2-4 The effect of the loss of detail in the representation of terrain as the grid size is increased (From Hengl, et al, 2006)	42
Figure 2-5 Schematic representation of the scaling methods interpolation, extrapolation and upscaling (After: Bierkens <i>et al.</i> , 2000)	43
Figure 3-1 The Study area in Bedfordshire, UK. The elevation data are OS Land-Form PROFILE™ tiles (© Crown copyright Ordnance Survey All rights reserved) and the stream data are based on digital spatial data licensed from Centre for Ecology and Hydrology © CEH(© crown copyright (0186A)). The detailed map shows the location of the three field sites at which soil moisture was measured (Stone Hill, Church Meadow and Mox Farm)....	51
Figure 3-2 Photos showing the three field sites at which soil moisture was measured. (Top Left Stone Hill; Top Right, Church Meadow; Bottom, Mox Farm).....	52

Figure 3-3 Soil maps for each of the three experimental fields in the study area. Left: Maps produced at 1:10,000 scale by (Burton, 2003), Right: Biggleswade Sheet TL14 at 1:25,000 scale (Wright, 1987).....	54
Figure 3-4 Available soil maps at increasingly detailed scales from 1:250,000 soil association maps to 1:25,000 and 1:10,000 scale soil series maps.....	58
Figure 3-5 Delta-T weather station with wind vane, anemometer, net-radiometer, global radiation sensor, rain gauge, air temperature and relative humidity sensors.....	60
Figure 3-6 Diagrammatic representation of the MLURI soil moisture probe (From: Gaskin and Miller 1996).....	62
Figure 3-7 Principle of the Delta-T PR1 soil moisture probe (Delta-T Devices Ltd., 2001).....	62
Figure 3-8 Layout of the field surveys in Stone Hill in 2004 for each of the three sampling dates, showing the soil boundaries at 1:10,000 scale (Burton, 2003) and the GPS locations of the sampling points.....	64
Figure 3-9 Example of a Delta-T soil moisture Access Tube installed in Church Meadow showing the rubber cap and collar fitted in an attempt to prevent water entering the tube and bypass flow down the length of the tube.....	65
Figure 3-10 Locations of the 38 soil moisture access tubes installed in Stone Hill (22) (Top) and Church Meadow (16) (Bottom) The soil boundaries at 1:10,000 scale (Burton, 2003) are shown along with OS Land-Form PROFILE™ elevation data resampled to a 20 m grid	66
Figure 3-11 Description of the method used to calculate the critical upslope areas from the CEH 1:50,000 river data and the OS Land-Form PROFILE™ DTM.....	69
Figure 4-1 (a) Monthly rainfall data for 2003-2005 compared to the 30 year average (1970-2000) compiled from weather stations at Silsoe and Woburn, Bedfordshire (b) Cumulative monthly rainfall data for 2003-2005 compared to the 30 year average (1970-2000) compiled from weather stations at Silsoe and Woburn, Bedfordshire.....	73
Figure 4-2 Surface soil moisture measurements (Top 100 mm) in Stone Hill, Church Meadow and Mox Farm. Taken using Delta-T ML2 ThetaProbe.....	76
Figure 4-3 Daily rainfall data (Data from Stone Hill weather station) for the time periods prior to the surface soil moisture sampling. Vertical lines highlight the sampling dates in the relevant fields (a) 2004 (b) 2005.....	77
Figure 4-4 Results from ANOVA by sample date, bars show the 95% confidence intervals on the mean. (a) Stone Hill, 2004 (b) Church Meadow, 2005 (c) Mox Farm, 2005.....	79
Figure 4-5 Results from ANOVA by soil series for each sampling date, bars show the 95% confidence intervals on the mean. (a) Stone Hill, 2004 (b) Church Meadow, 2005 (c) Mox Farm, 2005	82

Figure 4-6 Indices in each of the three experimental fields (a) SSWI (b) DYNWI (c) SWRSS. The left 3 figures show the sub-catchment and field boundary of Mox Farm. The right 3 figures show the sub-catchment and field boundaries of Church Meadow at the top of the catchment and Stone Hill at the bottom of the catchment. (10*Vertical exaggeration).....	83
Figure 4-7 Description of the methods used to obtain the data required to generate regression models for analysing soil moisture distributions	84
Figure 4-8 Variance in measured surface soil moisture explained by SSWI, DYNWI, SWRSS and SSWI+SWRSS for each of the eight soil moisture field surveys.....	85
Figure 4-9 Variation in surface soil moisture explained by a combination of soils and Terrain indices for each of the eight sampling dates in Stone Hill, Church Meadow and Mox Farm. Variables included in the Soil + Terrain models can be found in Table 4-1	88
Figure 5-1 Locations of the 38 soil moisture Access tubes in Stone Hill (Top) Church Meadow (Bottom) Access tube numbers are those referred to in the text. The background map is the 10:,000 scale soil map for each of the fields.	94
Figure 5-2 Results from soil moisture access tube measurements (Tube 21) for the beginning and end of the season in (a) 2003 and (b) 2004	96
Figure 5-3 Results from soil moisture access tube measurements (a) Tube 12 (b) Tube 13 in 2003 (The red line shows approximate saturated water content)	97
Figure 5-4 Daily rainfall and average daily temperatures (Data from Stone Hill weather station) for the time periods prior to the weekly soil moisture sampling at the Access tubes (a) 2003 (b) 2004	99
Figure 5-5 Average soil moisture (% vol/vol) in Stone Hill 2003 for each sampling date at 100 mm and 1 m. Error bars show the standard error on the mean.	102
Figure 5-6 Relative differences from the field mean soil moisture for Stone Hill 2003. Error bars represent +/- Standard deviation of the difference over the growing season.....	105
Figure 5-7 Results of the ANOVA for soil moisture average soil moisture in Stone Hill 2003 with respect to (a) Depth (b) Soil texture at the measurement point (LS-Loamy Sand SCL-Sandy Clay Loam S- Sand CL-Clay Loam SZL-Sandy Silt Loam SC-Sandy Clay) (c) 1:10,000 scale soil series. Error bars show the 95% confidence interval	107
Figure 5-8 Average soil moisture (% vol/vol) in Stone Hill 2004 for each sampling date at 100 mm and 1 m. Error bars show the standard error on the mean.....	108
Figure 5-9 Relative differences from the field mean soil moisture for Stone Hill 2004. Error bars represent +/- Standard deviation of the difference over the growing season.....	111
Figure 5-10 Results of the ANOVA for soil moisture average soil moisture in Stone Hill 2004 with respect to (a) Depth (b) Soil texture at the measurement point (LS-Loamy Sand SCL-Sandy	

Clay Loam S- Sand CL-Clay Loam SZL-Sandy Silt Loam SC-Sandy Clay) (c) 1:10,000 scale soil series. Error bars show the 95% confidence interval	113
Figure 5-11 Average soil moisture (% vol/vol) in Church Meadow-2003 for each sampling date at 100 mm and 1 m. Error bars show the standard error on the mean.....	115
Figure 5-12 Relative differences from the field mean soil moisture for Church meadow in 2003. Error bars represent +/- Standard deviation of the difference over the growing season ...	118
Figure 5-13 Results of the ANOVA for soil moisture average soil moisture in Church Meadow 2003 with respect to (a) Depth (b) Soil texture at the measurement point (LS-Loamy Sand SCL-Sandy Clay Loam S- Sand CL-Clay Loam SZL-Sandy Silt Loam SC-Sandy Clay) (c) 1:10,000 scale soil series. Error bars show the 95% confidence interval.....	119
Figure 5-14 Photograph of Stone Hill showing (1) Flat area at the top of the field (2) Most steeply sloping area (3) Base of the field adjacent to the water course	120
Figure 5-15 Spearmans Rank Correlation Matrices for 100 mm depth for Church Meadow and Stone Hill (See Appendix VI for full details).....	123
Figure 6-1 The two approaches to the application of the STAMINA model, showing how terrain variables are input into a micrometeorological module (Index based or Energy balance) which links to a soil hydrology module and then into the crop growth module. The concept was then to improve the index based approach based on a regression estimator	125
Figure 6-2 The three indices used in the index method for applying the STAMINA model at a regional level. Shown for the 10 km ² study area in Bedfordshire	125
Figure 6-3 The principles behind CAS (Behrens et al., unpublished)	127
Figure 6-4 Methodology for selecting representative catchments (a) Showing the use of the SSWI and the improvement in the representation of the Study Area between using one catchment and 3, shown by plotting the CDI index from CAS (Behrens, 2003 personal communication) (b) Selecting an increased number of catchments increases the number of soils that are represented. The masked areas show areas less than 3° slope.....	129
Figure 6-5 CAS run for SWRSS (Top) SWRSS divided into 100 classes (Middle) The CDI results from running CAS for each of the representative catchments (Bottom) and The maximum CDI for all of the catchments (Bottom) The masked areas show areas less than 3° slope	131
Figure 6-6 CAS run for SSWI (Top) SSWI divided into 100 classes (Middle) The CDI results from running CAS for each of the representative catchments (Bottom) and The maximum CDI for all of the catchments (Bottom) The masked areas show areas greater than 3° slope	132
Figure 6-7 Histograms of the SSWI and SWRSS for a 50 m grid size for (a) The study area greater than 3° slope (b) The areas in the representative catchments greater than 3° slope	133
Figure 6-8 Indices and soil series boundaries for the three representative catchments.	134

Figure 6-9 Modelled yield for the Physically based and Index versions of the STAMINA model for the 3 representative catchments for 2003 and 2004	136
Figure 6-10 Histograms of yield (kg/ha) from the three representative catchments for the physically based and index based approaches to the STAMINA model.....	137
Figure 6-11 Modelled yield for the Physically based and Index versions of the STAMINA model for the three representative catchments for 2004 showing areas with above and below 6000 kg/ha	137
Figure 6-12 Yield in the physically based and index based models for 2004 (a) Shows the regression equation (b) shows the groupings of soil series in the two approaches	139
Figure 6-13 The yield for 2004 using the Index based STAMINA model and the regression estimate. The Difference images show the difference in yield between the Index and the regression estimate and hoe these relate to the soil boundaries (Top) and Elevation (Bottom).....	140
Figure 6-14 Variance explained by SSWI and SWRSS and Soil Series at 1:25:000 scale in the output yields predicted by the Index and Physically based STAMINA model.	141
Figure 7-1 Rainfall and drainage measured at each of the five lysimeters during the lysimeter study at Silsoe (Brown <i>et al.</i> , 1997) compared to the drainage modelled in the STAMINA model using the SWC and FC drainage functions.....	151
Figure 7-2 Root Mean Square Error (RMSE) between the measured and modelled drainage using SWC and FC drainage functions in the STAMINA model	152
Figure 7-3 Yield distributions for the representative catchments in the study area using the SWC and FC drainage functions in the STAMINA model	153
Figure 7-4 Yield maps for the representative catchments in the study area using the SWC and FC drainage functions in the STAMINA model.....	153
Figure 7-5 (a) Modelled soil water content for the (b) Modelled water content for the Enbourne Lysimeter. Using the SWC and FC drainage functions. The field capacity and wilting point shown are the values calculated by HYPRES pedotransfer function in the STAMINA model.	155
Figure 8-1 Maximum, minimum and mean values of the three indices used in the STAMINA model over the 10 km ² study area at increasing DTM grid sizes.....	161
Figure 8-2 SSWI and SWRSS for each of small catchments containing the field sites at grid sizes from 20 m to 100 m.....	163
Figure 8-3 Maximum minimum and mean yield values modelled using the Index based STAMINA model for the 10 km ² study area at grid sizes from 50 m to 1 km	165
Figure 8-4 Root Mean Square Error (RMSE) between yield modelled at 50m using 1:25,000 scale soil series data and yield modelled at 100 m, 200 m, 500 m and 1km grid sizes using	

1:25,000 scale soil series data and at 50 m grid size using 1:250,000 scale soil association data.	165
Figure 8-5 Yield maps output from the STAMINA model using (a) Grid sizes 20 m, 100 m, 200 m, 500 m and 1 km and 1:25,000 scale soil series data (b) 50 m grid size and 1:250,000 soil association data.....	166
Figure 8-6 Root Mean Square Error (RMSE) between yield modelled at 50m using 1:25,000 scale soil series data using the Physically based STAMINA model and the FC drainage function and yield modelled at 50 m, 100 m, 200 m, 500 m and 1km grid sizes using 1:25,000 scale soil series data using the Index Based approach and at 50 m grid size using 1:250,000 scale soil association data and the Index based approach and yield modelled at 50m using 1:25,000 scale soil series data using the Physically based STAMINA model and the SWC drainage function	169

List of tables

Table 3-1 Soils descriptions for the soils in Stone Hill and Church Meadow at 1:10,000 scale (Soil Survey Bulletins).....	55
Table 3-2 Crop rotations in Stone Hill Church Meadow and Mox Farm over the soil moisture measurement campaigns	57
Table 3-3 Description of the soil parameters required for running the STMINA model.....	59
Table 3-4 Delta-T sensor descriptions and units of measurements (Delta-T, 2004)	60
Table 3-5 Sampling dates and locations for the eight surface soil moisture surveys.....	63
Table 3-6 Summary table showing a subset of the critical upslope areas and the corresponding length of the river network and how this differs from the length of the CEH river centre line data over the 100 km ² study area.....	68
Table 4-1 Regression models explaining the largest proportion of variation in surface soil moisture for each of the eight sampling dates in Stone Hill, Church Meadow and Mox Farm. Model (i) Terrain + 1:10,000 soil data (ii) Terrain + 1:25,000 scale soil data (Figure 4-8 shows the variance in soil moisture explained by each of the models).....	86
Table 5-1 Access tube measurement locations excluded from analysis. Figure 5-1 shows location of the points in the field.	95
Table 5-2 Variance explained by soil properties and depth	106
Table 5-3 Variance explained by soil properties and depth	112
Table 5-4 Variance explained by soil properties and depth	116
Table 7-1 Predicted and measured water contents.....	156
Table 7-2 Crop Water Stress Index (CWSI) calculated from the STAMINA model for the Enborne and Cuckney Lysimeters	157

List of abbreviations

AWC-Available Water Content
CAS-Computer Aided Sampling
C-Clay
CDI-Cumulative frequency Distribution Index
CEH-Centre for Ecology and Hydrology
CLAPAS- CLassement de Paysages et Segmentation
CL-Clay Loam
CSIRO-Commonwealth Scientific and Industrial Organisation
CWSI-Crop Water Stress Index
DTM-Digital Terrain Model
DYNWI-Quasi-Dynamic Wetness Index
EC-European Commission
ET-Evapotranspiration
EU-European Union
FC-Field Capacity
GIS-Geographic information System
LAI-Leaf Area Index
LS-Loamy Sand
MARS-Monitoring Agriculture with Remote Sensing
NSRI-National Soils Resources institute
OM-Organic Matter
OS-Ordnance Survey
PC-Profile Curvature
PWP-Permanent Wilting Point
RMSE-Root Mean Square Error
SCL-Sandy Clay Loam
SC-Sandy Clay

SL-Sandy Loam

S-Sand

SSWI-Steady State Wetness Index

STAMINA-STability And MitigationN of Arable systems in hilly landscapes

SWC-Saturated Water Content

SWRSS-Short Wave Radiation on a Sloping Surface

SZL-Sandy Silt Loam

(δ_{ij}) -Relative difference from the mean for each sample point in the field

$(\overline{\delta_{i,j}})$ -Bias of the location with respect to the mean field soil moisture

$\sigma(\delta_{ij})$ -Standard deviation of (δ_{ij})

1 Introduction

1.1 Agriculture and climate change

Agriculture in the 15 member states of the European Union (EU) (as at August, 2003) employed on average 4% of the population (Eurostat, 2005). In the United Kingdom (UK), in 2003 it employed over half a million people and contributed £7.9 billion to the economy. In the UK 77% of the total land area is used for agriculture and almost 20% for arable crops (Office of National Statistics, 2005). It is therefore important to understand both the processes that influence crop yield and assess the risks to farming in the context of the projected changes in climate. The National Union of Farmers (2005) state that:

“It is critical to an industry so dependent on climatic conditions to be aware of the changes and how to tackle them”

The general trends in the UK climate are expected to be that

- CO₂ concentrations and temperatures increase;
- Precipitation decreases in the summer and increases in the winter months;
- There will be an increase in the occurrence of extreme events (Hulme *et al.*, 2002).

An example of such an extreme event occurred in the summer of 2003, when a severe drought significantly decreased the yields in crops across Europe (EC, Joint Research Centre, 2003). Changes in climate are not only expected to influence yield but also management practices in agriculture. Many of the expected changes are linked to soil water contents (National Union of Farmers, 2005). These include:

- Decrease in summer soil moisture resulting in an increased need for irrigation;
- Increased drainage to prevent water logging;
- Inability to work the land without damaging soil structure.

It is important for scientists to understand soil water dynamics in agricultural land and how these may change as a result of changes in climate. This knowledge can then be used to offer advice to farmers and policy makers on management strategies to mitigate against the risks for farming in the future. These risks have been identified as particularly important in hilly landscapes (Richter *et al.*, 2003). This research examines water dynamics in hilly agricultural land and assesses the effect of water availability on crop yields in hill slopes using modelling techniques.

1.2 Impact of terrain on agriculture

Crop yield in undulating and hilly landscapes, has been shown to be a function of soil properties, including texture and drainage characteristics. These factors control soil available water (Irmak *et al.*, 2001, Pachepsky *et al.*, 2001). Soils often display properties in the form of topo-sequences where properties are linked to terrain due to the development and movement of soils within slopes (Brady and Weil, 1998). The change in drainage properties down a slope is also a recognised phenomenon and groups of soils with the same parent material which display this characteristic are known as a soil catena (Brady and Weil, 1998). It follows then if yield is a function of soil properties and soil properties are driven by terrain that yield should be significantly correlated with terrain variables. This has been shown in several studies (Zeleeke *et al.*, 2004, Pachepsky *et al.*, 2001). Iqbal *et al.*, 2005 showed that a combination of terrain and soil properties explained up to 80% of the yield at a field scale.

Climate is a major driver of crop growth. In hilly landscapes the climatic effect is modified by topography. Hence the relationship between landscape characteristics and yield is important as it changes the risk of farming in hilly landscapes compared to farming in areas of low relief. The relative spatial distribution of yield in an area is not necessarily stable in time. It is noted that in depression areas and at the base of hill slopes, excess water can cause very low yields in wet years (Pachepsky *et al.*, 2001, Kravchenko and Bullock, 2002, Kaspar *et al.*, 2004,) and yet these can be the most productive in dry years, the converse being true of convex areas (Jaynes *et al.*, 2003). The variability of

yield within a field is shown to be higher in years of increased water stress (Kravchenko *et al.*, 2005) and it is suggested that topographic effect on yield is at a maximum in extreme meteorological conditions and topography (Kravchenko and Bullock, 2002).

1.3 STAMINA project – context

Crop growth and crop yields have been shown to be a function of terrain in many small scale academic studies as outlined in the previous section. A national assessment as part of the STAMINA project (STability And MitigationN of Arable systems in hilly landscapes) (<http://www.rothamsted.bbsrc.ac.uk/aen/stamina/>), which is a European Commission (EC) funded project (Project Number: EU-QLK-2002-01313) based on extensive long term arable farming records in Romania, clearly showed the effect of terrain on the agricultural productivity of land. This showed the effects of slope and aspect on yield values, with south facing and shallower slopes showing higher yield values. This study was one of the major drivers in the STAMINA project (Simota, 2006, personal communication).

The ability to predict drought or water logged conditions gives the potential for the classification of land as suitable or unsuitable for agricultural use (Naden *et al.*, 2000). STAMINA, examines the modelling of crops within hilly landscapes (Box1.1). Traditionally crop growth models assumed a flat surface the new approach in the STAMINA project was to create a model that accounted for the variation in crop growth which was driven by terrain. The aim was to create a model that could be run for past and future climate scenarios at a regional level and to assess the changes in yield and other agro-meteorological indicators at a regional extent (Richter *et al.*, 2003). The new approach taken in STAMINA integrates crop, micrometeorological and soil water balance models with a Digital Terrain Model (DTM) in a Geographic Information System (GIS) environment. This then leads to the development of risk indicators for crop growth, which include the effects of terrain.

In order contribute to the understanding of the risks of farming in hilly landscapes the STAMINA model needs to be run at a regional level. If this is possible then the model can be used to make assessments and inform policy makers of changes which may occur in the future, as a consequence of climate change, and to estimate how those potential changes, outlined in section 1.1, will effect hilly regions. In its current form the model is too complex to run at a regional level as it takes several days to run for a few hundred cells. The first part of this research addresses the drivers of the spatio-temporal variability in soil moisture and how data available at increasing spatial extents affects the ability to model these variations. The second part investigates a method to apply the STAMINA model at a regional extent and addresses the issues of scale and data availability.

The STAMINA project team agreed that an index based approach was the most appropriate way to simplify the model formulation in order to apply it at a regional extent and developing this method was a deliverable of the STAMINA project. However regional simulations using the STAMINA model have not yet been undertaken due to problems with code development and issues linked to more general model formulation. Some of these were analysed as part of this research and are outlined in chapters 6 and 7. The work carried out for this thesis is set in the context and challenges of continual model development. The detailed sensitivity analysis outlined in chapters 6 and 7 was developed by the author from problems in the model formulation identified in collaboration with project partners.

"Climate change is very likely to enhance drought and temperature stress, which – as both are exponents of the energy and water balance – are likely to be exacerbated by terrain. The interaction between agro-climate and terrain has not been implemented in models to assess the impact on arable crops. Uncertainty in crop production needs spatial resolution to an ecologically and practically useful scale to be meaningful for land use planning (sub-region).

Therefore, our overall objective was to improve quantitative methods for assessing the sensitivity of arable agro-ecosystems in Europe. To achieve this objective and obtain physical and bio-physical evidence for this interaction we have:

(a) down-scaled and calibrated an agro-meteorological model in hilly terrain,

(b) implemented this model into a crop growth model and evaluated it at large field and catchment scale, and

(c) linked the integrated model to terrain-derived input variables and derived a series of Agro-Environmental Indicators (AEI) related to crop performance and sustainability.

(d) These AEI were generated for several case studies in Europe and communicated to various groups of potential users and stakeholders.

This last objective involved the participation of institutions analysing the farming practices and regionalisation techniques."

Box 1-1 Extract from the executive summary of the STAMINA final report showing the aim and objectives of the overall STAMINA project (Richter *et al.*, unpublished)

1.3.1 STAMINA model – overview

This section gives an overview of the STAMINA model, which links crop growth to terrain. It outlines how it was developed and how terrain is included in the modelling process. This will be contrasted in this thesis with an alternative method to model this interaction, developed to apply the model at a regional level. The calculation methods of the DTM parameters used in the original (physically based) STAMINA model were developed by the author in collaboration with Rana and Ferrera in 2004.

Traditionally crop modelling has assumed a flat surface with meteorological inputs being the same at all points in the landscape. The principle behind the STAMINA model is that meteorological conditions vary within hill slopes. For example, in the northern hemisphere, a south facing slope will receive more radiation than a north facing slope. These varying meteorological values will consequently influence the yield at a given point in the landscape. The STAMINA model takes meteorological values measured at

the lowest point in the catchment and calculates individual inputs for the crop growth model based on the terrain characteristics at each cell within the slope (Figure 1.1).

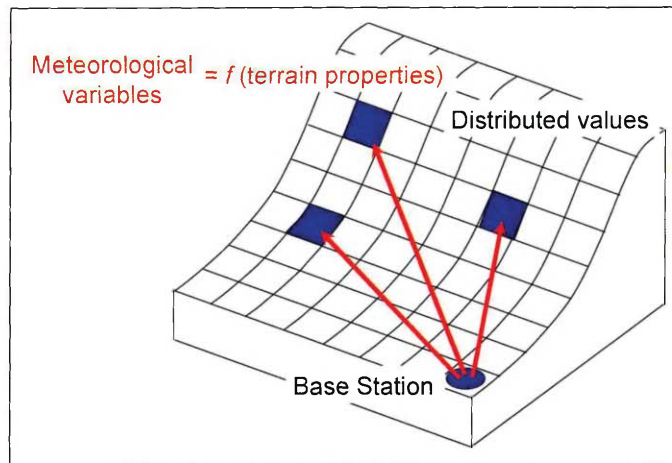


Figure 1-1 The principles of the Micro-Meteorological part of the STAMINA model. Data recorded at a the lowest point in a catchment are distributed in the catchment based on topographic variables

1.3.2 The physically based approach to the STAMINA model

The physically based STAMINA model works on a grid based system. Here each cell is defined by:

- Topographic parameters;
- Soil properties;
- Crop information.

The model has three key components:

- **A micro-meteorological module**, which manipulates meteorological variables measured at a base station and distributes them to each cell in the landscape, based on the topographic parameters. This module uses a physically based approach to distribute:
 - Wind speed and direction;
 - Global and net radiation;

- Soil, latent and sensible heat fluxes;
- Air temperature
- **A soil hydrology module** which vertically distributes water through the soil profile and calculates drainage from the base of the profile. The formulation of this part of the model is based on the physical properties of the soil;
- **A crop growth module**, which simulates the growth of the crop based at each cell based on meteorological parameters and water availability.

The physically based approach in the STAMINA model requires each cell in the landscape to be characterised by a series of parameters. These parameters are then used in the equations which describe the physical processes. These were calculated using LandMapRTM, a suite of software for automatically classifying landforms into landform facets using a high-resolution Digital Terrain Model (DTM). LandMapRTM gave a wide range of shape parameters which could be manipulated to define the landscape with respect to physical processes. In the model formulation the relative and absolute location of a cell within a slope is defined by its horizontal and vertical distances from stream or ridge cells. The topographic features, in this context, are defined by the flow paths of water from a ridge cell to a stream cell. Figure 1-2 shows the definition of the absolute distances calculated for each cell.

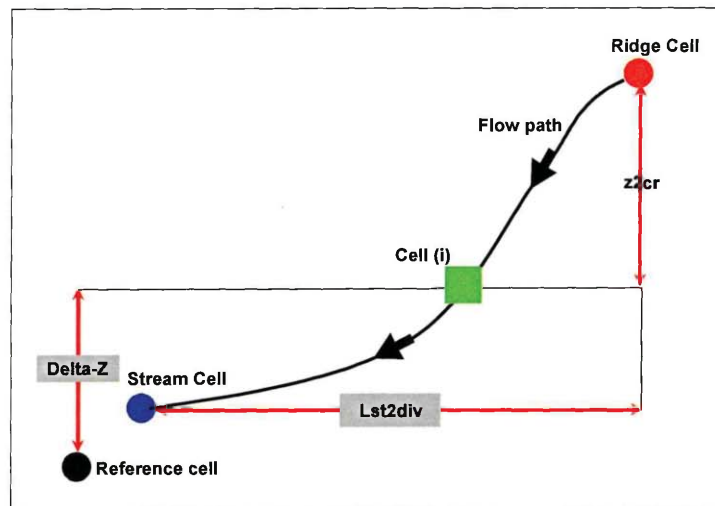


Figure 1-2 The topographic parameters required for defining a cell in the landscape for input into the physically based STAMINA model

The calculated for input into the STAMINA model are:

- The vertical height difference between a given cell and the ridge above that cell. This was given by the “z to crest (z2cr)” parameter in LandMapRTM;
- The “half length of the hill”. This is given by half the “stream to divide length (Lst2div)” in LandMapRTM;
- Slope and aspect calculated directly by LandMapRTM and converted from degrees to radians for input into the model;
- “Delta Z” is calculated by subtracting the height of the base station from each cell in the area to be modelled.

The shape of the landscape is also required for the calculation of wind speed and wind direction. The calculations combine the profile curvature and the percentage of the vertical distance between the stream and the ridge any cell represents. A series of logical statements are then applied to classify the landscape into either “step”, “regular” or “irregular” (Figure 1-3):

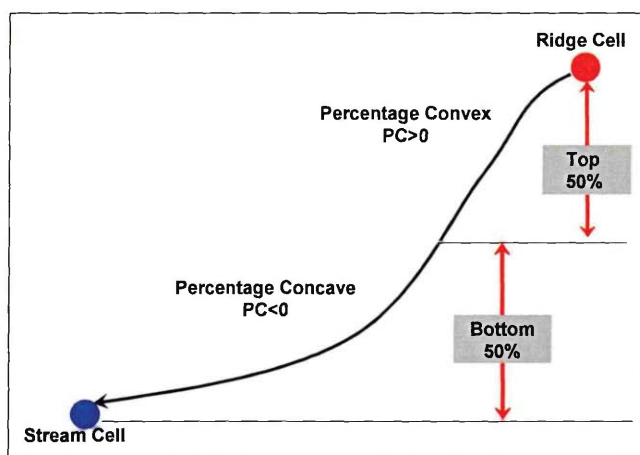


Figure 1-3 The definition of the "shape" of the landscape in the STAMINA model as based on the percentage of land in the upper and lower parts of the hillslope that are convex or concave (In profile curvature)

- **IF** more than 50% of land within a catchment is convex (Profile curvature >0) then the catchment is "step" shaped;
- **IF** more than 50% of the cells in the top 50% of catchment are convex (Profile curvature >0) AND more than 50% of the cells in the bottom part of the catchment are concave (Profile curvature <0) then the catchment is defined as "regular";
- **IF** neither of these criteria is fulfilled then the landscape is "irregular".

1.3.3 The problem

The STAMINA model, as it stands, uses complex physically based approach to distributing the major controls on evapotranspiration (ET), global radiation, wind speed, wind direction and temperature as a function of terrain. This is the approach outlined in section 1.3.2. The model cannot be run in its current form at a regional level due to the processing time for a large number of grid cells. If the grid size were increased to reduce the number of cells the representation of the landscape, including small areas which may have significant topographic characteristics, would be lost. An approach is required to apply the model at a regional level while maintaining the key controls on crop growth

within the landscape. The aim was to use regional meteorological stations and generate distributed parameters across a regional level (Figure 1-4).

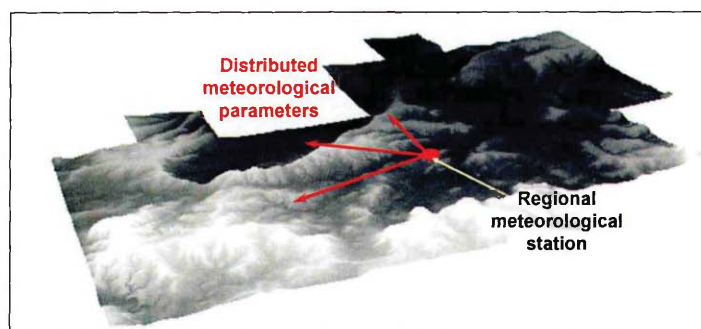


Figure 1-4 The principle of applying the STAMINA model at a regional level based on data measured at a regional meteorological station

1.3.4 The approach adopted

In an attempt to apply the STAMINA model at a regional level the approach taken is to assume that the key controls on crop growth that will vary with landscape position are water availability, global radiation and temperature. The method selected was to change the form of the energy balance approach for distributing micro-meteorological parameters to an index based approach (Figure 1-5). The research carried out by the author and detailed in this thesis investigates the use of indices which take into account the flow and accumulation of water in the landscape, the variability of solar radiation and temperature but to assume wind speed, wind direction and heat fluxes are constant as a function of terrain. The index based approach replaces the energy balance module by a simple scaling of meteorological variables measured at the reference point (Figure 1-4). Two methods are available for modelling the vertical movement of water in the STAMINA model:

- The ISBA approach (Figure 1-5) is linked to the energy balance module and models drainage from the top 100 mm and from the base of the profile at 1 m. The top 100 mm in this approach is the layer which interacts with the atmosphere. This approach requires hourly meteorological inputs;

- The cascading approach (Figure 1-5) models drainage between 100 mm layers to a depth of 1 m and then drainage from the base of the profile. This option can be run for daily meteorological inputs.

Both of these options are available when using the physically based model but only the cascading approach is available in the index based model. This is due to the different formulations of the index and ISBA approaches. In addition the index based approach is designed to be run for daily meteorological data.

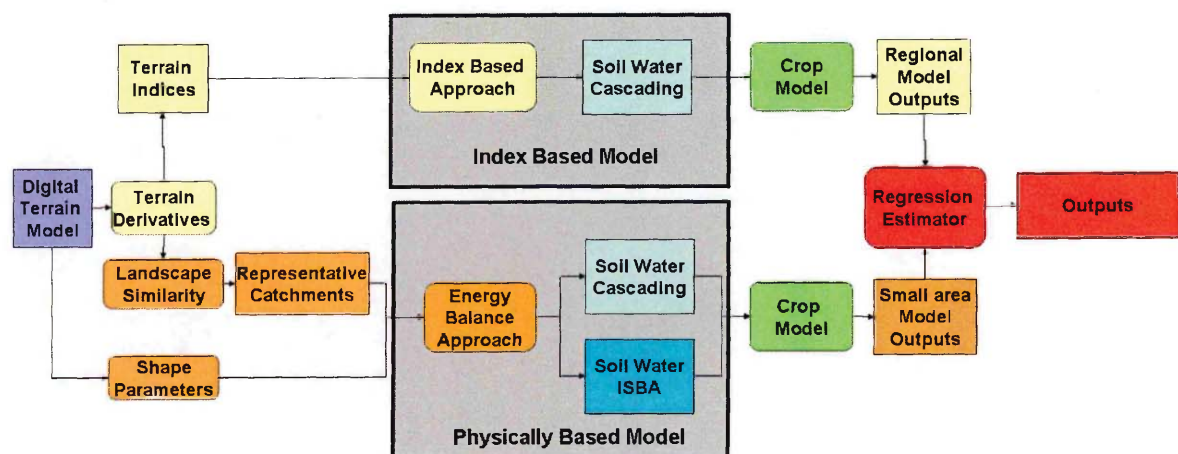


Figure 1-5 The two approaches to the application of the STAMINA model, showing how terrain variables are input into a micrometeorological module (Index based or Energy balance) which links to a soil hydrology module and then into the crop growth module. The concept was then to improve the index based approach based on a regression estimator.

1.4 Aim and objectives of this thesis

1.4.1 Aim

The aim of this thesis is to model soil moisture in the landscape, in time and space and incorporate these results into a method of applying the STAMINA model at a regional level.

1.4.2 Objectives

- **Objective 1:** To investigate data sets and methods which can be used to model the controls on soil moisture in the landscape and to determine the scales at which they are available for use;
- **Objective 2:** To collect field data in order to develop regression models to explain the spatial and temporal variability of soil moisture within the STAMINA field sites;
- **Objective 3:** To develop models which explain soil moisture variation in the landscape using data available at different spatial scales;
- **Objective 4:** To develop a method of applying the STAMINA model at a regional level based on the analysis of soil moisture in the landscape;
- **Objective 5:** To apply sensitivity analysis to the regionalised modelling approach and to assess the appropriateness of the model in the light of the data available at a regional level;
- **Objective 6:** To assess the methods developed in the light of available data and the potential use for the modelling of risk in agriculture.

1.5 Development of this thesis

This thesis is divided into eight further chapters. These chapters reflect the ongoing development of the STAMINA model and the direction taken by the project throughout the period of work on this thesis. Chapters 4 and 5 focus on the analysis of the data from the field experiments set up as part of the STAMINA project and seeks to answer some of the research questions posed in the literature about the spatial and temporal drivers of soil moisture. The second part focuses on the development of the method to apply the STAMINA model at a regional extent and issues that occurred during the model development and that I was required to address as part of my involvement with the STAMINA project.

Chapter 2 reviews the literature regarding the spatial distribution of soil moisture in the landscape. The discussion covers:

- The distribution of soil moisture in the landscape, the methods by which it has been modelled and the limitations imposed by the lack of data available at large spatial extents;
- The temporal nature of soil moisture in the landscape and the concept of temporal stability of spatial patterns;
- The indices that have been developed in an attempt to model soil moisture
 - Their application and success within the fields of hydrological modelling
 - Their ability to estimate distributed soil moisture in the landscape;
 - Methods which have been implemented with the aim of improving the predictions of distributed soil moisture in time and space.
- The software which is available to calculate topographic wetness indices
- The effect of DTM grid size and soil data availability on the ability to accurately represent terrain based processes

An aim of this project is to apply the STAMINA model at a regional level. The second part of the literature review outlines:

- Methods which can be used for the regional application of data and models
- The selection of representative sites for the comparison of two versions of the STAMINA model followed by a brief discussion on the software available to do this.

Chapter 3 outlines the methods used in this study. This includes:

- A description of the Bedfordshire (UK) study area and the data available for modelling the variability of soil moisture at different scales
- The field methods used to monitor the spatio-temporal evolution of soil moisture in the study area. Two field experiments are discussed:
 - Surface soil moisture surveys;
 - Profile probe measurements.
- An outline of the methods used to process the digital terrain data in order to calculate the indices required, including a description of the software.

Chapter 4 presents the results from the eight surface soil moisture surveys carried out in 2004 and 2005. It includes an analysis of the results in time and space with respect to soil data and terrain indices. It also examines the effects of data availability at different spatial extents and the effect this has on our ability to characterise the spatial variability of soil moisture in the landscape.

Chapter 5 presents the results from the soil moisture access tubes over the 2003 and 2004 growing seasons. It includes analysis of the temporal stability of soil moisture. It examines soil moisture variability with respect to soils series, depth, and soil textural class.

Chapter 6 outlines:

- The development of the method for applying the STAMINA model at a regional level;
- The method by which representative study sites were chosen and the results of this analysis;
- The results, in terms of yield variability, of the comparison between the two versions of the STAMINA model;
- The results from using a regression approach to adapt the results of the regionalised STAMINA model based on the physically based STAMINA model;
- A comparison of the drivers in the index and physically based versions of the STAMINA.

Chapter 7 presents the results of the sensitivity analysis of the physically based STAMINA model to the drainage function used.

Chapter 8 presents the results of the sensitivity analysis of the regionalised STAMINA model with reference to grid size and soil scale.

Chapter 9 presents the conclusions of this research:

- The implications of the soil moisture results on developing a regionalised STAMINA model;
- The drivers of soil moisture in the landscape and how these compare to the drivers in the STAMINA model;
- The issue data availability and the impacts on spatially distributed modelling;
- Further work required.

2 Literature review

2.1 Soil moisture – an introduction

Soil moisture influences many phenomena ranging in scale from the likelihood of flooding to the nature and structure of microbial communities (Killham, 1994) (Figure 2-1). These factors affect land management, which in turn impacts the value of land. It is therefore important to understand the processes which control the movement of water in the landscape and determine its magnitude at a given location.

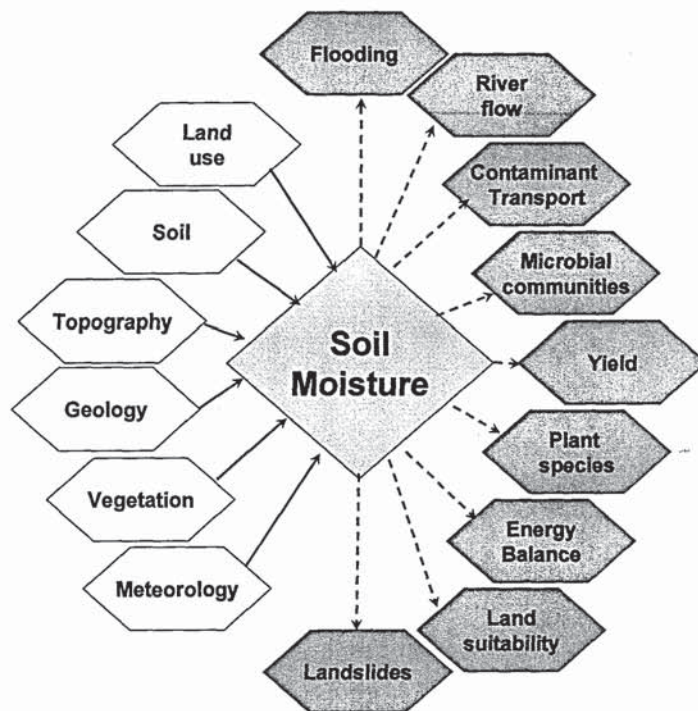


Figure 2-1 The factors in the landscape that drive soil moisture and can be used to predict it (Left) and the phenomena that it influences (Right)

The processes which control soil moisture are in turn driven by a series of spatially variable landscape characteristics (Figure 2-1). Since the affects of soil moisture potentially have significant economic implications, not just for farming, it is valuable to model the relationship between soil moisture and measurable landscape attributes. The

purpose of modelling these processes is to aid predictions of destructive events and to highlight areas vulnerable to their effects. The following discussion outlines the:

- **Effect of soil moisture** on landscape phenomena;
- The **processes** which are responsible for the transfer of water between the atmosphere, soil and drainage features;
- The **temporal variations** in soil moisture;
- The **measurement of soil moisture** and the problems associated with available measurement techniques;
- The **measurable factors** which can be used to explain the spatial organisation of soil moisture in the landscape;
- The **development of indices** which attempt to model the distribution of soil moisture in the landscape;
- The **computer software** available for the calculation of these indices.

2.2 Effects of soil moisture

Soil water makes up less than 0.1% of the fresh water stored on the earth's surface (Alley *et al.*, 2002). However it is a key state variable in the terrestrial hydrological cycle.

It controls the **partitioning of energy** at the earth's surface as it determines the balance between sensible heat (direct heat transfer) and latent heat (heat transfer through water vapour) fluxes (GSWP, 2004). Since it controls these fluxes it has also been suggested that it may influence **precipitation** at a continental scale (Salvucci *et al.*, 2002). At a seasonal and continental scale Shukla and Mintz, (1982) showed that increased spring soil moisture lead to increased summer precipitation although Salvucci *et al.* (2002) argue that at shorter time scales the soil moisture effect is not the direct cause of increased precipitation.

Water content in the soil determines soil properties such as infiltration capacity which in turn influences the extent to which precipitation **infiltrates** into the ground or **runs off** directly into streams and rivers (Beven and Wood, 1983). It has been shown that the existence and spatial distribution of saturated areas can have a large impact on storm flow. Modelling has indicated that in variety of circumstances a spatially organised pattern of soil moisture predicts much higher peak runoff values (Schmidt *et al.*, 2000.) These all lead to soil moisture conditions being a major **driver in flood risk** in a catchment.

The availability of soil moisture has an influence on **vegetation distribution** (Breshears and Banes, 1999). For example Ma *et al.*, (2004) concluded that land in a semi-arid valley in China was not suitable for reforestation, but should instead be replanted with shrubs, as the soil moisture content was not high enough to support tree growth. From an anthropogenic perspective soil moisture conditions influence **contaminant transport** (Frankenberger *et al.*, 1999) and the **potential for erosion and landslides** (Borga *et al.*, 2002).

2.3 Processes which control soil moisture in the landscape

The amount of water entering the soil profile depends on the infiltration capacity of the soil. Infiltration is driven by two forces: the suction gradient and gravity. The infiltration capacity decreases with increasing soil water content (Rowell, 1994). The rate of movement through the soil decreases as soils dry out, as the unsaturated hydraulic conductivity is decreased at higher matric potentials (Lal and Shukla, 2004). The upward movement of water through the soil is linked to moist subsoil below drier topsoil (Rowell, 1994). Water leaving the soil profile by evaporation from the soil surface or transpiration from plants is primarily driven by meteorological conditions: solar radiation, temperature, humidity and wind speed. Evaporation is at a maximum at increased soil water contents and on hot sunny days with dry winds.

Horizontal flow in the landscape that contributes to stream flow is outlined by Dingman, (2002). The horizontal movement of water down slope is split into three types. The first is overland flow. This is either a function of soil moisture in the profile exceeding saturation (Saturation overland flow) or rainfall intensity exceeding infiltration capacity (Hortonian overland flow). The second is subsurface flow in the unsaturated zone. This is both flow through the soil matrix and bypass flow through macro pores in the soil profile. The third is flow in the saturated zone. This comes from groundwater or perched saturated zones in the soil profile

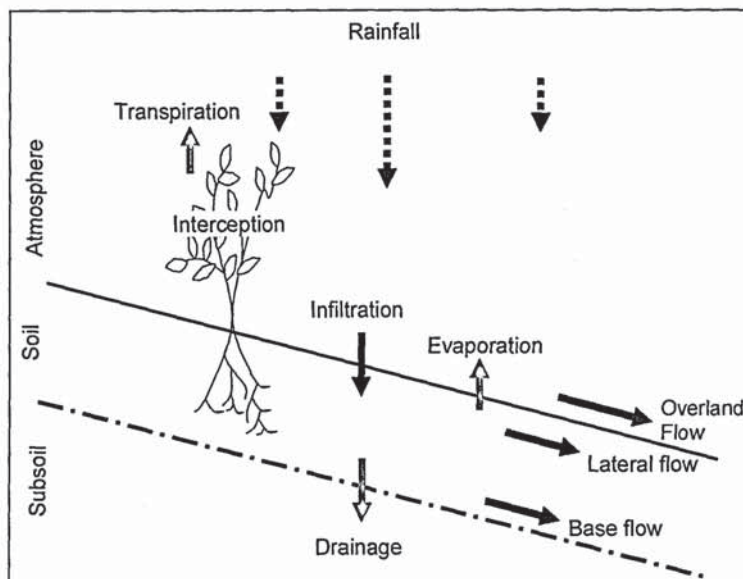


Figure 2-2 The processes which drive soil moisture in the landscape (Adapted from Rowell, 1994)

2.3.1 Temporal variation of soil moisture

An analysis of the spatio-temporal dynamics of soil moisture is important for the understanding of the processes that control it. It is proposed that if time stable sites which represent the average soil moisture in an area can be located then large scale field sampling campaigns can be reduced to a few representative locations (Western and Grayson, 1998). Time stable sites are those at which the relative soil moisture is time invariant with respect to spatial location. The ability to identify the temporal persistence

of a spatial pattern is particularly important in setting up monitoring networks to validate airborne and satellite measured soil moisture over large footprints (Mohanty and Skaggs, 2001, Cosh *et al.*, 2006, Starks *et al.*, 2006). If stable patterns of soil moisture can be identified they can also be used in a more efficient use of water resources. If certain areas are identified as consistently dry these can be the focus of irrigation measures (Starr *et al.*, 2005)

The first analysis of the temporal stability of soil moisture was by Vachaud *et al.*, (1985). Two forms of analysis were used. These have been used subsequently by other authors in other situations.

The **first** was to calculate the relative difference ($\delta_{i,j}$) (Equations 2-1) from the mean soil moisture for each sample point in the field. The mean value of the relative difference ($\overline{\delta_{i,j}}$) gives an estimate of the bias of the location with respect to the mean field soil moisture and the standard deviation ($\sigma(\delta_{i,j})$) is an estimate of temporal stability (Vachaud *et al.*, 1985).

$$\begin{aligned}\Delta_{i,t} &= S_{i,t} - \overline{S_t} \\ \overline{S_t} &= \frac{1}{n} \sum_{i=1}^n S_{i,t} \\ \delta_{i,t} &= \frac{\Delta_{i,t}}{\overline{S_t}}\end{aligned}\quad \text{Equations 2-1}$$

Where:

$S_{i,t}$ – Soil moisture at a point, i , at time t ;

$(\overline{S_t})$ – Spatial average soil moisture at time t ;

$\Delta_{i,t}$ – Difference between the soil moisture at a location i at time t to the mean soil moisture in an area at time t ;

The mean soil moisture in an area can be estimated by a measurement at a location with a low standard deviation and a known bias (Grayson and Western, 1998). The **second** method of analysis used by Vachaud *et al.*, (1985) is to calculate Spearman's Rank Correlation Coefficient (r_s) (Equation 2-2) for each date with respect to every other date in the monitoring period. A high Correlation Coefficient indicates that each point in the field is consistently higher or lower than each of the other locations.

$$r_s = 1 - \frac{(n-1) \sum_{i=1}^n (R_{i,t} - R_{i,t'})^2}{n(n^2 - 1)} \quad \text{Equation 2-2}$$

Where:

- r_s – Spearman's rank correlation co-efficient between the measurements at time t and t' ;
- n – The number of measurement points at the time t ;
- $R_{i,t}$ – The rank of the a measurement at point i and time t with respect to the other measurements at time t ;
- $R_{i,t'}$ – The rank of the a measurement at point i and time t' with respect to the other measurements at time t' .

In the surface layer Parent *et al.*, 2006 show that at a 48 hour to 1 week time scale soil moisture is associated with the periodicity of rainfall events and at a two week scale the length of dry spells. Lauzon *et al.*, (2004) also showed that soil moisture was driven by the periodicity of rainfall events at a 1 to 16 day time scale and viewed at a longer time scales soil moisture was driven by a seasonal effect.

If time stable sites are to be used for soil moisture monitoring and if they are to be selected a priori for an experiment or monitoring network then it is important to be able to identify the physical characteristics of those sites (Jacobs *et al.*, 2004).

Since the Vachaud *et al.* (1985) study several further studies have been carried out, which analyse the spatio-temporal patterns in soil moisture in the landscape. In general these more recent studies show that the mean relative difference is up to $\pm 50\%$ and the standard deviation is up to $\pm 30\%$ (Jacobs *et al.*, 2004, Cosh *et al.*, 2006, Lin, 2006, Starks *et al.*, 2006). Martínez-Fernández and Ceballos, (2003) have higher standard deviations and this could be because their study area is much larger than the others, at 1285 km² and that the sites within this area are hydrologically independent. These are all much larger than the values given by Vachaud *et al.*, 1985.

The general principles that come from these studies are that:

- Temporal stability is linked to soil texture (Vachaud *et al.*, 1985, Starks *et al.*, 2006), although the exact nature of this link is not consistent between studies;
- Both the consistency in time of the spatial pattern and the temporal stability of a given point with respect to the mean soil moisture increase with depth. This is to be expected as the influence of biological and climate conditions is expected to decrease with depth (Martínez-Fernández and Ceballos, 2003);
- The persistence of the spatial pattern of soil moisture is a function of soil topography and cropping patterns (Jacobs *et al.*, 2004).

2.4 Water and plant growth

Water in the soil is held in three types of pores (Rowell, 1994):

- Macropores $> 50 \mu\text{m}$. Water will drain freely from these pores and when they are filled the soil is said to be saturated. Once the macropores are empty the soil is at Field Capacity (FC). This is the point at which the suction gradient acting upwards is balanced by the gravitational head acting down. For well structured British soils this is taken to be a matric potential of -5 kPa (White, 1997);

- Micropores 50-0.2 μm . Water is stored in these pores and is removed by evaporation and transpiration from plants. Once the micropores are empty the soil is said to be at Permanent Wilting Point (PWP) as at this point there is no further water available for plant growth. This is defined as a matric potential of -1500 kPa;
- Residual micropores <0.2 μm . This water, which is strongly bound to soil particles and is not available for plant growth. It is mostly associated with clay particles. This, in general is water held at matric potentials less than -1500 kPa.

The Available Water Content (AWC) (Equation 2-3) for plant growth (Lal and Shukla 2004) in a soil is defined as:

$$AWC = FC - PWP \quad \text{Equation 2-3}$$

The AWC also not only depends on the matric potential at which water is held in the soil but also on the ability of a plant to adapt to changing water potentials. Furthermore the water held in the soil between FC and PWP is not always equally available to a plant for growth, in fact this is only the case if most of the water is available at low suctions and if atmospheric conditions do not force excess ET from the plant (White, 1997)

The available water content of soils is positively correlated with soil Organic Matter (OM) as this increases the FC of soils. The clay content of soils does not have a large impact on the AWC of soils as increasing clay content leads to both an increase in FC and PWP. FC is also a function of aggregation and structural porosity of a soil. (Lal and Shukla 2004)

2.5 Controls on soil moisture

There is agreement that a wide variety of interconnected factors influence soil moisture distribution, with different factors being of varying importance at different scales (Hawley *et al.*, 1983, Bárdossy and Lehmann, 1998, Rhode and Seibert, 1999, Gómez-

Plaza *et al.*, 2001, Florinsky *et al.*, 2002, Pallindo, 2002, Svetlitchnyi, 2003, Romano and Fu *et al.*, 2003, Cantòn *et al.*, 2004, Ma *et al.*, 2004, Romshoo, 2004, Hébard *et al.*, 2006). The main factors outlined in the literature are outlined below.

Terrain properties including slope, aspect, curvature, elevation, landform classes

Terrain controls the flow of water in the landscape, in the surface and to a lesser degree in the subsurface (Western *et al.*, 2004) It is seen as a critical factor in any attempt to model soil moisture throughout the landscape (Reid, 1973). It has been identified as the key to the cost-effective modelling of soil moisture distribution due to the wide availability of DTMs at high resolution for large spatial extents. In the UK the Ordnance Survey (OS) provides coverage with Land-Form PROFILETM data at a 10 m grid size.

In unsaturated conditions topography is said to control rainfall redistribution to give the observed patterns observed in the landscape (Nandakurma, 1994, Romano and Pallindo, 2002). Topography also controls many pedogenic processes, such as the development of clay and organic matter. These then have an influence on soil properties, for example soil hydraulic conductivity, and consequently soil moisture (Leenhardt *et al.*, 1994, Svetlichnyi, 2003). Moore *et al.* (1993) suggest that the spatial variation of soil properties may be captured in terrain attributes. In more extreme terrain, topography controls climate, vegetation and soil development to a greater extent (Wang *et al.*, 2002).

Landform classes (e.g. ridges, valley bottoms, depression areas) display differing topographic and soil characteristics. Their ability to explain the variance of soil moisture (Park and van de Giesen, 2004) highlights the interaction of processes that occur to give many of the patterns that we observe in the landscape (Hawley *et al.*, 1983).

Soil properties and lithology

It is apparent that topography is not the sole factor controlling soil moisture and that other factors influence both water redistribution and the loss of water from the soil. The importance of soil properties as a major driver of soil moisture, has been suggested in

many recent studies (Pellenq *et al.*, 2003, Ridolfi *et al.*, 2003, Buttle *et al.*, 2004, Buttafuoco *et al.*, 2005, Wilson *et al.*, 2005, Lin *et al.*, 2006a). The physical properties of soils control both hydraulic conductivity and water retention. The water retention properties subsequently influence the amount of evapotranspiration that occurs from the soil surface, further influencing soil moisture (Western *et al.*, 2004).

Rhode and Seibert, (1999) suggest that both the topographic variation in an area and also the underlying geology influence the occurrence of Mires in two Swedish study sites. They suggest that Geology modifies the topographic effects in an area. The underlying geology influences the deep drainage characteristics in an area. In areas of shallow bedrock the lithology has the potential for creating preferential flow paths due to changes in hydrological characteristics from the overlying soil

Vegetation and land use

The vegetation distribution, rooting depth and surface cover all control evapotranspiration and evaporation from the soil, Several studies have shown that as vegetation increases throughout the growing season this decreases the influence of topography on soil moisture (Kang *et al.*, 2000, Western *et al.*, 2002, Cantón *et al.*, 2004).

Further to this, Hébard *et al.*, 2006 suggest that the primary control on soil moisture in landscapes with significant human influence, in particular the drainage networks, is in fact the land management processes, and that other local controls such as topography and insolation are not major drivers of the soil moisture.

Meteorology

Several meteorological factors influence soil moisture these include precipitation, solar radiation and wind speed both directly and also through their affect on evapotranspiration. Meteorological conditions vary in any landscape and are often a function of terrain. These factors will have an impact on rainfall reaching the ground,

solar radiation and temperature, all of which have an impact on evapotranspiration and the vertical movement of water in the soil profile.

2.6 Modelling soil moisture variation

The hydrological response of a catchment to rainfall is a function of runoff rate, infiltration rate and precipitation characteristics (Figure 2-3). These are in turn driven by topography, surface properties, soil and vegetation within the catchment (Hawley *et al.*, 1983, Aryal *et al.*, 2003, Buttle *et al.*, 2004). The distribution of precipitation as runoff or infiltration is determined by the antecedent soil moisture conditions.

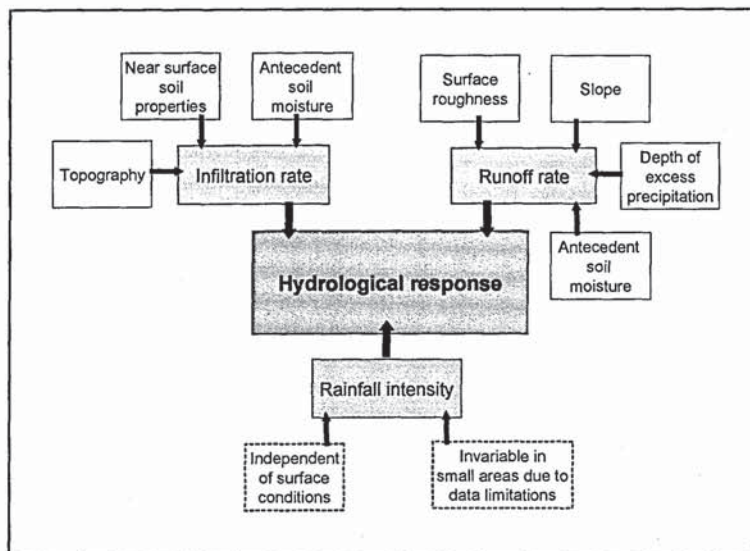


Figure 2-3 Factors that influence the hydrological response of a catchment (After Hawley *et al.*, 1993)

2.7 Indices for distributed soil moisture modelling

2.7.1 Terrain based wetness Indices

Several terrain based Wetness Indices have been developed in an attempt to highlight the distribution of soil moisture, based on simplified representations of the physical processes

that are occurring in the landscape, including the key factors that control it (Barling *et al.*, 1994). The understanding that terrain is significant in explaining soil moisture variation has been the foundation for the development of topographic indices (Moore *et al.*, 1991). Two similar indices have been developed. The **first** comes from the TOPMODEL approach outlined above. The equation (Equation 2-4) is based on a grid representation of the landscape (Beven and Kirkby 1979):

$$\omega = \ln \left(\frac{a}{\tan \beta} \right) \quad \text{Equation 2-4}$$

Where:

- ω – Topographic wetness index;
- a – The upslope area draining through a point (m^2);
- β – The slope of the surface (mm^{-1}).

Five key assumptions and limitations in the wetness index approach of TOPMODEL are outlined in Beven, (1997):

- Steady state down slope surface discharge occurs. The discharge is a product of average discharge and specific catchment area;
- The local hydraulic gradient can be approximated by the slope of the ground surface;
- The saturated hydraulic conductivity decreases exponentially with depth in the soil profile;
- Steady state conditions apply within the catchment;
- The catchment has spatially uniform soil properties.

Two further relationships are also implied by the Steady State Wetness Index (SSWI) in the TOPMODEL framework (Wilson and Gallant, 2000):

- Locations in the catchment with the same topographic wetness index have the same ratio between the local and mean depths to the water table;
- Points with the equal values of SSWI will respond in the same way to a given rainfall input.

Beven (1997) also suggests that to obtain the best results from the SSWI there needs to be a shallow soil overlying impermeable bedrock.

The **second** set of indices, based on similar assumptions, has been developed from work by O'Loughlin *et al.* (1981) (Equation 2-5) and includes some parameters, which define soil hydraulic characteristics. The equation is based on an irregular grid derived from contours (O'Loughlin *et al.*, 1986):

$$W_s(x, y) = \frac{1}{MbT} \int q dA \quad \text{Equation 2-5}$$

Where:

- W_s – Steady State Wetness Index;
- M – Slope (mm^{-1});
- b – Length of the contour base of the element (m);
- T – Local Transmissivity (*Saturated Hydraulic Conductivity*Soil Depth*) (m^2d^{-1});
- q – Net subsurface drainage flux (md^{-1});
- A – Upslope catchment area (m^2).

Both these indices are based on the steady state assumption. This is rarely achieved in practice due to recharge rates within a catchment being spatially non uniform. Factors such as evaporation from the soil profile mean that all the water from the physical

upslope area does not reach a given cell (Beven, 1997, Western *et al.*, 1999, Aryal *et al.*, 2003).

Topographic wetness indices have been developed further and versions applicable to a non steady state proposed. Barling *et al.*, 1994 proposed a quasi-dynamic wetness index based on the steady state wetness index of Beven *et al.*, 1979. Nandakurma *et al.*, 1994 have proposed a transient wetness index based on the work of O'Loughlin (1981), (1986). These both use the concept of effective upslope area (Equation 2-6), that is the area drained within a given time period (Equation 2-7). As time increases these indices tend towards the prediction of the SSWI.

$$A_e = \frac{A_i}{b} \quad \text{Equation 2-6}$$

Where:

- A_e – Specific upslope area per unit contour width (m);
- A_i – Effective contributing area (*determined by following each drainage path upslope and accumulate drainage time until it reaches a specified time*) (m^2);
- b – Flow width (m).

$$t_{EF} = \int_E^F \frac{\eta}{\kappa_s \tan \beta} ds \quad \text{Equation 2-7}$$

Where:

- t_{EF} – Time required for water to travel from E to F along a flow line (d);
- κ_s – Saturated hydraulic conductivity (md^{-1});
- η – Effective porosity (m^3m^{-3});
- β – Slope of impermeable boundary (*assumed to be slope of the soil surface*) (mm^{-1});
- s – Horizontal distance between E and F (m).

2.7.2 Terrain based radiation indices

It is also possible to define indices which represent the distribution of temperature and radiation in the landscape. Radiation drives a series of processes such as evapotranspiration and plant growth (Kumar *et al.*, 1997). Terrain modifies radiation inputs at the surface, hence the determination of radiation received at a point requires either a dense network of measurement stations or a modelling approach to distribute values measured at a base station (Duguay, 1993). Kumar *et al.*, (1997) suggest that empirical approaches are only suitable where a point value is required. The alternative methods that have been developed to overcome this problem use parameters derived from a DTM to calculate the distribution of radiation across a wide area.

Out of the several packages that calculate wetness indices the Terrain Analysis Program for Environmental Science – Grid based (TAPES-G) suite of software also calculates radiation and temperature for sloping surfaces. The following discussion outlines the principles behind the temperature index and shortwave radiation on a sloping surface as calculated by the TAPES-G Solar Radiation module (SRAD) (Further details can be found in Appendix I). SRAD calculates radiation and temperature on a daily basis for a period of the year as specified in the input file. It then outputs average values for this specified time period. The output is a single value for each grid cell of a DTM. The approach used to calculate short wave radiation incident on a sloping surface is outlined in Wilson and Gallant (2000).

Extra-terrestrial solar irradiance is adjusted for transmittance of the atmosphere using a lumped transmission approach. The direct beam (including diffuse radiation from within 5° of the direct beam) is then adjusted for a sloping surface and added back to the diffuse beam. This adjustment is based on:

- The angle between the beam and the normal to the slope;
- The effect of shading based on obstruction of the direct beam by the surrounding landscape;

- Reflected radiation received from sites facing a given cell. This is a function of shading and the albedo, of the surface.

SRAD adapts both the direct and diffuse beam radiation based on long term monthly averages of cloud transmission and sunshine fraction data for the area modelled. On sloping sites the cloud transmittance is also adjusted for the effects of shading and the multiple reflections that occur between the land surface and the clouds.

The approach used to calculate Short Wave Radiation on a Sloping Surface (SWRSS) is outlined in Wilson and Gallant, 2000. Both direct beam and diffuse beam solar radiation are calculated from extra-terrestrial solar irradiance incident outside the earth's atmosphere. These are adjusted for the transmittance of the atmosphere using either a lumped transmission approach or calculations that account separately for scattering and absorption by water vapour and other molecules within the earth's atmosphere (Equations 2-8).

$$R_{diff} = (0.271 - 0.294\tau^m)R_{oh}$$

$$R_{oh} = \frac{1}{r^2} \cos \Phi \cos \delta + \cos \Phi \sin \delta \cosh$$

Equations 2-8

$$R_{dirh} = R_{oh}(\tau_{SL} + (t_{lapse} * elev))^m$$

Where:

- R_{oh} – Amount of sunlight incident on a point just outside the earth's atmosphere ($\text{KJm}^{-2}\text{d}^{-1}$);
- r – Ratio of earth-sun distance to its mean;
- Φ – Latitude of the observer ($^{\circ}$);
- δ – Declination of the sun ($^{\circ}$);
- h – Hour angle of the sun from solar noon ($^{\circ}$);

- R_{dirh} – Direct beam short wave irradiance incident on a flat surface under clear skies ($\text{KJm}^{-2}\text{d}^{-1}$);
- R_{difh} – Diffuse beam short wave irradiance incident on a flat surface ($\text{KJm}^{-2}\text{d}^{-1}$);
- τ_{SL} – Ratio of the radiation incident at the top of the atmosphere incident on the earth's surface (*Transmission co-efficient at sea level*);
- m – Ratio of the path length in the direction of the sun at the zenith angle to path length in the vertical direction;
- t_{lapse} – Transmissivity lapse rate.

The data available for this project lead to the selection of the lumped transmission approach. There are two parts to the diffuse radiation, one which comes from within 5° of the direct beam and therefore varies as the sun moves across the sky and the second which comes equally from all parts of the sky. In order to accurately predict the radiation on a sloping surface the part which comes from within 5° of the direct beam part must be added back to the direct beam solar radiation and subtracted from the other, isotropic, diffuse radiation. This is done using the circumsolar fraction which specifies the proportion of diffuse radiation which comes from within five degrees of the direct beam and is an input parameter

The total short wave irradiance incident on a sloping surface is the sum of the diffuse, direct and reflected radiation adjusted for the effect of slope. The direct solar radiation is adjusted for slope based on the angle between the beam and the normal to the slope (Equation 2-9) and also for the effect of shading based on obstruction of the direct beam by the surrounding landscape.

$$R_{dirs} = R_{dirh} \cos i \quad \text{Equation 2-9}$$

Where:

- R_{dirs} – Direct irradiance on a sloping surface without shading ($\text{KJm}^{-2}/\text{d}^{-1}$);
- i – Function of δ , β , Φ , ψ and h (as in Equation 2-8).

This shading affect is calculated using the sky view fraction. The diffuse beam and reflected radiation are also adjusted based on the sky view fraction. This is the visible fraction of sky and is calculated based on horizon angles from profiles taken across the terrain. These are the averaged, for 16 discrete angles, around a given cell.

Reflected radiation in a sloping landscape is received from sites facing a given cell. This is a function, not only of the sky view fraction but also of the albedo, or reflective properties, of the surface (Equations 2-10).

$$\nu = \frac{1}{n} \sum_{\Phi=1}^n \cos H_{\Phi}$$

$$R_{ref} = (R_{dirh} + R_{difh})(1 - \nu)\alpha$$

Equations 2-10

Where:

ν - Sky view fraction;

H_{Φ} - Horizon angle ($^{\circ}$);

N - Number of cosine angles;

Φ - Directions at which the horizon angle is calculated;

α - Fraction of sunlight reflected from the surface (Albedo);

R_{ref} - Reflected radiation from other surfaces ($\text{KJm}^{-2}\text{d}^{-1}$).

All these fluxes defined above assume a clear sky. SRAD then adapts them based on long term monthly averages of cloud transmission and sunshine fraction data for the area modelled. On sloping sites the cloud transmittance is also adjusted for the sky view fraction and the multiple reflections that occur between the land surface and the clouds (Equations 2-11).

$$R_{th} = R_{dirh} + R_{difh} \left[\frac{n}{N} + \left(1 - \frac{n}{N} \right) \beta \right]$$

$$\beta_s = \beta_v \left(\frac{R_{tsns}}{R_{tss}} \right) \quad \text{Equations 2-11}$$

Where:

- R_{th} – Daily incoming solar radiation on horizontal sites ($\text{KJm}^{-2}\text{d}^{-1}$)
- n/N – Ratio of the observed duration of sunshine to the maximum possible for that place and date (Sunshine fraction)
- β_s – Cloud transmittance adjusted for the multiple reflections between the ground surface and clouds
- R_{tsns} – Total daily short wave radiation without shading ($\text{KJm}^{-2}\text{d}^{-1}$)
- R_{tss} – Total daily short wave solar radiation on sloping sites ($\text{KJm}^{-2}\text{d}^{-1}$)

These short wave radiation fluxes are calculated instantaneously at 12 minute intervals, symmetrical around solar noon and then summed over a day. The gridded output file is then average of all the days in the time period specified when the SRAD is run.

2.7.3 Terrain base temperature indices

The temperature in the landscape is modelled in SRAD using long term averages of maximum and minimum surface and air temperatures and lapse rates (Equation 2-12). Temperature is a function of elevation, Leaf Area Index (LAI) and the ratio of radiation received at a given point in the landscape to that on a horizontal surface (Equation 2-13).

$$T = T_b - \frac{T_{lapse}(z - z_b)}{1000} + C \left(S - \frac{1}{S} \right) \left(1 - \frac{LAI}{LAI_{max}} \right) \quad \text{Equation 2-12}$$

$$S = \frac{R_{ts}}{R_{th}} \quad \text{Equation 2-13}$$

Where:

- T – Temperature at a grid point ($^{\circ}\text{C}$);

- T_{lapse} – Monthly temperature lapse rate;
- T_h – Temperature at the reference station ($^{\circ}\text{C}$);
- z – Elevation of the grid cell;
- z_b – Elevation of the reference station (m);
- LAI – Leaf area index at the grid cell (m^2m^{-2});
- C – Constant = [1];
- S – Short wave radiation ratio at each point;
- R_{ts} – Daily total short wave irradiance on sloping sites ($\text{KJm}^{-2}\text{d}^{-1}$);
- R_{th} – Daily total short wave irradiance on horizontal sites ($\text{KJm}^{-2}\text{d}^{-1}$);

Equations and symbol definitions from (Wilson & Gallant, 2000).

2.8 Discussion of the use of terrain based indicators

There has been much discussion in the literature as to the assumption that terrain can be used as a single predictor for surface soil moisture. It is suggested that the evidence in the literature does not wholly substantiate the simple relationship between soil moisture and wetness index (Western *et al.*, 2004). The development of the wetness index was set in the context of hydrological modelling, in an attempt to predict runoff and consequently stream flow. In many cases, when used in hydrological modelling, it has been seen to perform well (Barling *et al.*, 1994, Beven, 1997). However, when it has been used to predict soil moisture in the landscape the results are less convincing (Beven, 1997, Western *et al.*, 2004). This suggests that the underlying processes controlling soil moisture are more complex and not just driven by terrain. Small scale processes may be linked to local surface heterogeneities causing flow convergence and divergence in the landscape (Burt and Butcher, 1985). It is also suggested that the dominant control on surface soil moisture may be evapotranspiration, linked to vertical water movement and not lateral sub-surface flow (Lamb *et al.*, 1997, Western *et al.*, 1999,). Furthermore the spatial variability of soil moisture may be linked to the soil structure and vegetation to a

greater extent than the flow processes represented by the wetness index (Nyberg, 1996). The ability of hydrological models, which use the wetness index, to give successful predictions of channel flow may be due to compensation by other parameters in the model and not necessarily the model's accurate prediction of the distributed soil moisture (Beven, 1997). In addition a more general reason for the lack of correlation between the wetness index and soil moisture may be that the assumptions on which it is based are not fully satisfied (Beven, 1997, Seirbit *et al.*, 1997)

The time varying component of soil moisture and the extent to which different topographic attributes and soils control soil moisture has been the source of much discussion. The general conclusions are:

- Spatial structure of soil moisture as defined by geostatistical methods changes with time (Romshoo *et al.*, 2004, Buttafuoco *et al.*, 2005);
- Increased water content reduces the variability of soil moisture content (Romshoo *et al.*, 2004);
- Variables defining the vertical movement of water in drainage and ET are more important in dry conditions (Western *et al.*, 1999, Peters-Lidard *et al.*, 2001, Pellenq, 2003);
- Variables defining the horizontal movement of soil moisture and infiltration are more important in wet conditions (Burt and Butcher, 1985, Western *et al.*, 1999, Gomez Plaza *et al.*, 2001, Peters-Lidard *et al.*, 2001, Aryal *et al.*, 2003).

An example of the difference in the prediction of soil moisture in dry versus wet conditions comes from analysis of the large Tarrawarra (*Catchment in Victoria, Australia*) data set (Western *et al.*, 1998). It shows that solar radiation indices dominate the explanation of variance in dry conditions, and that a combination of the steady state wetness index and solar radiation predict more variance in wetter conditions (Western *et al.*, 1999). Wilson *et al.*, (2005), again using the Tarrawarra data set, suggest that terrain

attribute weightings for regression models, which predict soil moisture, should be adapted depending on the average soil moisture within the profile. This study also suggests that residual patterns, not explained by terrain, are down to soil properties and vegetation characteristics. As in many studies there is not enough soils data at a sufficiently fine scale to be able to quantify these effects or draw conclusions as to their limitations. Further to this discussion it is suggested that soil properties are a major driver in soil moisture distribution (Crave and Gascuel-Odoux, 1997, Buttfuccio *et al.*, 2005) and that increasing the detail of soils data leads to improved estimates of soil moisture (Lin *et al.*, 2006a).

2.9 Software packages for calculating terrain indices

Several software packages are available to generate the parameters required to calculate terrain variables needed to model soil moisture from a DTM. Appendix II outlines the advantages and disadvantages of using a wide range of different packages. The decision as to which package to use in this study was based on both the potential use for modelling a wide range of drivers of soil moisture and the requirements of the STAMINA project. TAPES-G (Terrain Analysis Program for Environmental Sciences), a product developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) Australia, was selected for further use in this project. It consists of a set of modules, which use primary topographic variables calculated by the core program element. (Wilson and Gallant, 2000).

The reasons for selecting TAPES-G (Appendix II) are:

- It allowed a wide variety of terrain indices to be calculated within the same suite of software;
- It used a grid system which was required for further modelling;
- It allowed for the introduction of soils and multiple flow directions in wetness index calculations;

- It calculated indices without needing the flow parameters required for full hydrological models such as TOPMODEL (Beven and Kirkby, 1979) and TOPOG (Vertessy *et al.*, 1994).

2.9.1 TAPES-G

TAPES-G consists of a set of modules, which use primary topographic variables calculated by the core program element. The principle is that simplified physical models are then used to calculate parameters that represent hydrological, geomorphological and ecological processes. The simplification of physical models aims to maintain the key factors that control the processes, but sacrifice some of the physical complexity to obtain improved estimates of the spatial pattern in the landscape (Wilson and Gallant, 2000).

The core of TAPES-G calculates:

- Slope;
- Aspect;
- Flow Direction;
- Profile, Plan and Tangent Curvature;
- Upslope Area (Gallant and Wilson, 1996).

TAPES-G uses four methods to force the flow direction and hence alter the estimates of upslope area (the area draining into a specific cell) and representation of stream network.

The four methods are:

- **D8** Distributes flow to 1 of 8 adjacent cells with the steepest decent;
- **Rho8** Stochastic version of D8 with the expected direction as the aspect of the cell;
- **FD8/FRho8** Modifications of the above algorithms that allow water to flow to more than one adjacent cell. They weight the proportion of the water into each cell using slope;

- **DEMON** A method for routing water across cells in “stream tubes”, rather than on a cell by cell basis (Wilson and Gallant, 2000).

2.9.2 DYNWET-G

This module calculates two wetness indices based on both topographic and optionally soil properties. These aim to represent soil moisture distribution and saturation zones (Wilson and Gallant, 2000).

The steady state wetness index is the topographic wetness index used in TOPMODEL (Equation 2-4). This index requires:

- The upslope area, in this case is the total area, which drains into the cell (this can change with the flow direction algorithm used);
- The slope which represents the slope of the local hydraulic gradient.

The assumption made in the steady state wetness index is that the recharge occurs at a constant rate until equilibrium is reached in the catchment (Barling *et al.*, 1994).

The quasi-dynamic wetness index, instead of using total upslope area uses effective upslope area. This is determined by selecting the area that water would drain from in a specific time after a rainstorm event (Barling *et al.*, 1994). The quasi dynamic wetness index, in addition to topographic attributes requires three soil characteristics which represent the speed at which water moves through the soil profile. These are:

- Saturated Hydraulic Conductivity;
- Porosity;
- Soil Depth.

These parameters can be specified as constant over the catchment or as parameters varying, depending on the soil type, at a given location.

The drainage time is specified in the input parameters of this module and should be less than the time required for the catchment to reach equilibrium (Barling *et al.*, 1994, Wilson and Gallant, 2000).

2.9.3 SRAD

This module calculates:

- Short Wave Radiation Ratio;
- Short Wave Radiation on a sloping surface;
- Short Wave Radiation on a horizontal surface;
- Incoming atmospheric Long Wave Radiation;
- Net Long Wave Radiation;
- Net Radiation;
- Minimum, maximum and average air temperature;
- Surface Temperature (Wilson and Gallant, 2000).

The two parameters of interest in this study were distributed average temperature and SWRSS. The key equations and description of the calculations of these parameters are outlined in Section 2.7.

2.10 Grid size and soil scale

When working with DTM data, a key question that must be answered is “What resolution DTM is required?” This to some extent depends on the processes being modelled and the nature of the required results. For example, it has been shown that in TOPMODEL hydrological conductivity can be changed and this will compensate for the increase in grid size (Brassington and Richards, 1998) and still give acceptable stream flow estimates. However when examining spatially distributed terrain attributes it is noted that changing grid size changes both the statistical and spatial distribution of topographic attributes (Quinn *et al.*, 1995). Several specific observations have been made as to the effects of increasing the grid size of a DTM (Zhang and Montgommery, 1994, Brassington and Richards, 1998, Thielen *et al.*, 1999, Florinsky and Kurakova, 2000, Kumar *et al.*, 2000, Wilson and Gallant, 2000, Thompson *et al.*, 2001, Kienzie, 2004). These are that it:

- Decreases the average slope length;
- Increases the specific catchment area of a cell;
- Has a greater effect on second order DTM derivatives such as slope curvature than on first order derivatives;
- Changes the correlation coefficients with other environmental variables, including soil moisture;
- Changes flow directions and channel network representations;
- Changes the distribution of the topographic wetness index;
- Decreases the information content in the DTM;
- Aggregation of a high resolution DTM gives better results than a low resolution DTM.

One major conclusion from many studies is that grid sizes for hydrological applications should not be greater than the maximum slope length in an area as at this point a large amount of information is lost from the DTM (Figure 2-5) (Zhang and Montgommery,

1994, Beven, 1997). Figure 2-4 (Hengl, 2006) shows the loss of detail in the representation of terrain as the grid size is increased. The grid size is represented by the vertical bars and it can be seen that as it is increased from 0.5 to 2.5 m small variations in the topographic surface, shown here as a curved line are no longer represented accurately.

As discussed earlier the detail of the soil data included in hydrological modelling and soil moisture prediction is important. More detailed data has been shown to lead to better predictions. In soil landscape modelling it has been shown that the scale of soil and terrain data should be approximately the same to avoid bias in the results (Zhu et al., 1997, Quinn *et al.*, 2005)

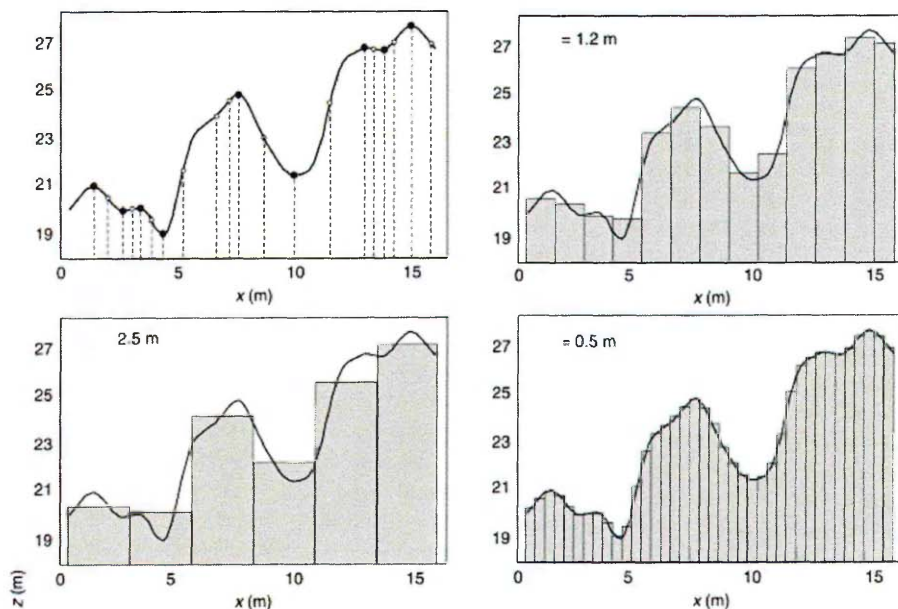


Figure 2-4 The effect of the loss of detail in the representation of terrain as the grid size is increased (From Hengl, et al, 2006)

2.11 Approaches to modelling at a regional level

The process of applying models at a larger scale is known in many cases as “up-scaling”. This may refer to changing the form of the model, interpolating or aggregating results or inputs. The term “up-scaling” is also applied to the application of field data results beyond the scale at which they were measured. There is much debate in the literature as

to the exact definition of the term ‘up-scaling’. One definition is the change in support or grid size using various methods of aggregation (McBratney, 1998). Bierkens *et al.* (2000) outline three specific changes in scale (Figure 2-5).

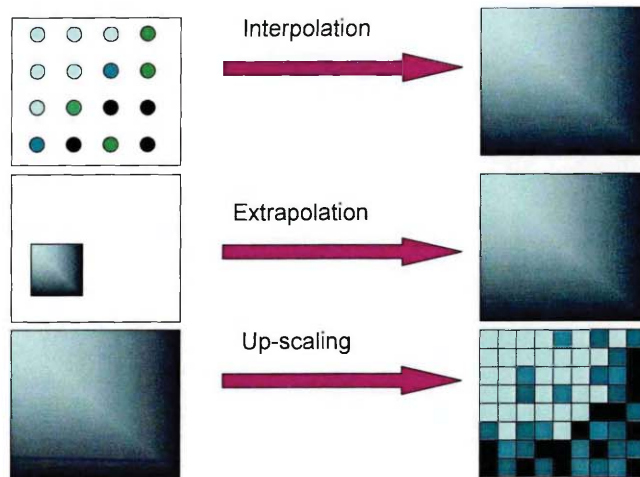


Figure 2-5 Schematic representation of the scaling methods interpolation, extrapolation and upscaling (After: Bierkens *et al.*, 2000)

In this discussion the term “up-scaling” will not be used due to its ambiguity and the more specific terms of interpolation, extrapolation, spatial aggregation and regional application of a model will be adopted. In the context of this study a method is sought by which the results of a model run over small areas of the landscape can be continuously applied at a regional level. The methods outlined above are all possible ways by which this could be achieved. However each has specific requirements regarding the form of the model and the data needed. The following discussion examines each of the methods and outlines the potential for its use in the regional application of the physically based approach to the STAMINA model

The first method outlined above, **interpolation**, requires autocorrelation between samples (Bierkens *et al.*, 2000). In the context of agricultural modelling with soils data there are hard boundaries in any soils data set at which it is expected that there will be a step change in the response of the model. In the case of this study the model relies on soils data and therefore interpolation is not an appropriate method for the regional application

of the model as the soil boundaries in the data will change with the input scale of the soils data.

The method of **extrapolation** requires the sampled or small areas that have been modelled to have characteristics representative of the region in which the model is to be extrapolated. If meaningful relationships between model results or field data in a small area and variables contiguous at a regional level, such as DTMs, can be developed there is no theoretical reason why they cannot be applied at a larger extent. This assertion requires the processes acting in the small area to be those acting in the wider landscape (Bierkens *et al.*, 2000).

Aggregation of model inputs, in this case of the grid size of the DTM needs to maintain and still be representative of the structure of the landscape (Kienzle, 2004). In landscape studies it is suggested that the absolute maximum for grid size, and the point at which information is lost is the typical hill slope length in the area (Brassington and Richards, 1998). When model inputs are aggregated consideration should be given to the proportion of land in a reference area with a given attribute and the frequency distributions of variables, ensuring that they do not change significantly as grid size is increased (De Vries *et al.*, 1998, Kienzle, 2004).

In the case of a model applied at a regional level it may be necessary not only to aggregate the model inputs and to develop relationships in order to extrapolate the model results, but to simplify the model (Bierkens *et al.*, 2000). Lark and Stafford (1998) suggest that any regionalised model or classification scheme should maintain the ability to predict variables correctly at a reference point. In relation to modelling this statement needs to be carefully considered as the more complex model designed for running at a small scale is often more vigorously calibrated and validated. Caution however needs to be used when the form of the model is changed as the processes represented in the two versions may not be the same. In this case the predictions of the two models may vary at a given reference point. This variation may assist in the interpretation in that it may highlight where modelling different processes predicts more precisely the state at any given point.

A proposed method of adapting the results of a simplified approach is to use a regression, or meta-model as used in the MARS (Monitoring Agriculture with Remote Sensing) project (Taylor *et al.*, 1997). This method would make use of the more specifically calibrated results of the complex physically based approach combined with the regional application of the simplified model. This approach is only applicable if there is a significant relationship between the two model outputs in areas that represent the landscape characteristics at a regional level.

A major consideration in the regionalisation of any model is the data available at any specific extent. In the case of this study in England and Wales the availability of DTM data is not a problem. The Ordnance Survey (OS) provide national coverage at a 10 m grid size. Soils data for England and Wales (available from the National Soils Resources Institute (NSRI)) however, is only available:

- At a national level at 1:250,000 scale;
- For certain 10 km square OS tiles are mapped as individual soil series at 1:25000 scale;
- For individual fields and small areas mapped as soil series at 1:10000 scale.

The STAMINA model also relies on meteorological data, which in the UK is only available for regional meteorological stations at a daily time step. If the STAMINA model is to be applied at a regional level it needs to be in a form that can use the data sets, available at that scale. (King *et al.*, 1998). Stein *et al.*, (2001) also notes that when the results of a regionalised model are interpreted the scale that they represent needs to be considered.

2.12 Selecting representative areas in the landscape

In the context of this study the physically based version of the model can only be run on small areas of the landscape. Consequently an approach is needed by which areas of the landscape can be classified based on their similarity or differences to the surrounding areas in order to select areas, which are representative of the wider landscape. Areas, which are then identified as being different, can be selected for concurrent use of the two

modelling approaches. The following discussion outlines some of the approaches used to define areas of the landscape based on specific pre-defined characteristics or numerical attributes, which fall into distinct groups in a feature space.

Original hierarchical classifications of landform elements were based around geomorphological features and landscape development. The basis of these initial classifications was terrain, geology, soils and vegetation (Howard and Mitchel, 1980). It can also be important to characterise the landscape for specific purposes based on a set of distinct physical characteristics (Shreier and Lavkulich, 1978, Thwaites and Slater, 2000). These descriptors may not correspond directly to geomorphological units, and hence numerically based classification schemes are important (Shreier and Lavkulich, 1978).

The methods that have been developed to undertake these landscape classifications were initially photo interpretation and manual classification and have developed to more numerically based approaches which combine varying data sets (Shreier and Lavkulich, 1978). A lot of work on landscape classification has centred on the use of clustering techniques, and more recently the use of fuzzy clustering. This is the process by which the outputs from the classification are not crisply classified into a specific class, but where each pixel is classified in terms of different degrees of membership to each of the defined classes (Irvin *et al.*, 1997, Lagacherie *et al.*, 1997, De-Bruin and Stein, 1998, Burrough *et al.*, 2000, MacMillan *et al.*, 2000b, Thwaites and Slater, 2000, Lui and Samal, 2002,). However clustering simply divides the landscape into similar regions and although this could be used in the project it does not indicate the degree to which a subset of the region is representative of the whole.

In the context of this study landscape elements need to be defined which are different from each other, but together represent the geomorphological characteristics of the region which is being modelled. A limitation of numerically based approaches is they do not take into account the knowledge of geomorphological features such as major catchments or changes in superficial geology or soils. It is therefore important to visually assess any classification or the results of a process by which similar or different areas are defined.

Two pieces of software exist, both which use the principle of defining similar areas of the landscape based on the similarity of histograms of terrain properties in a given area to those in a moving window passed across the landscape. The two software packages, CAS (Computer Aided Sampling) (Behrens, (2003) personal communication) and CLAPAS (CLAssement de Paysages et Segmentation) (Robbez-Masson, 1994, Lagacherie *et al.*, 2001) were compared as part of an MSc thesis (Skinder, 2005) for the area used in this study. It was concluded that they both gave similar results, but that CAS was simpler to use. CAS is used in this case to select representative small sub-catchments which together represent the topographic characteristics of the area. Two main similarity comparisons are used in CAS. The first is a modified version of the χ^2 test (Equation 2-14), which compares the relative frequencies of the variable in the base map to that of the reference area. The second is a new cumulative distribution index (CDI) based on cumulated frequency distributions (Berhens *et al.*, unpublished).

$$\chi_m^2 = \sum_{i=1}^n \frac{(rO_i - rP_i)^2}{rP_i} \text{ Equation 2-14}$$

Where:

χ_m^2 – Modified Chi² based on percentages and adjusted for no data values

rO_i – Relative frequency in the reference map

rP_i – Relative frequency in the window of the base map.

The results of the CDI are applied to each cell in the landscape. The value given to each cell is the basis of the comparison of the histogram of values in the window around it, of user defined size, and the histogram of values in the reference area. The values are between zero and one with one being the most similar to the reference area and zero being the least similar.

2.13 Summary

In summary the literature points to soils being a major driver in the spatial distribution of soil moisture at a small catchment scale. It also suggests that detailed soils information is

the key to understanding hydrological processes within slopes. It is suggested that the distribution of soil moisture using soil maps at increasingly detailed scales will generate models that improve the prediction of soil moisture. The literature also points to the interaction of soils with terrain and therefore further analysis of how these interact in the modelling of soil moisture is required.

Furthermore the use of indices to distribute rainfall and solar radiation in the landscape needs to be investigated, including an assessment of the most appropriate wetness index to use to distribute rainfall in the index approach to the STAMINA model.

The aim of the STAMINA model is to simulate yield distributions in hilly landscapes based on parameters calculated from a DTM. The literature suggests that at increasing grid sizes a DTM will lose the detail of terrain features. It is therefore important to apply a sensitivity analysis of the STAMINA model to grid size to obtain the appropriate level of detail required for model outputs. In the light of the investigations in the literature it is also suggested that soil properties may also have a significant impact on the distribution of crop yield. Hence detailed sensitivity analysis of the STAMINA model to soil properties is required, particularly as in modelling at a regional level there is a lack of detailed soils information.

3 Materials and Methods

3.1 Introduction

Field work was carried out as part of this study to examine the dynamics of soil moisture within the landscape. This chapter outlines the methods used in the field component of this study. It then addresses the DTM data processing that was required to create the indices required for analysis of the field data and running the STAMINA model. There are three components:

- **Field site descriptions** and the **data** available for analysis and modelling;
- Outline of the **soil moisture sampling** both: soil moisture vertical profiles and surface measurements;
- **DTM data processing** including running TAPES-G, SRAD and DYNWET-G for the study area;
- **Description of the Lysimeter experiments** (Brown et al, 1997)

3.2 Site description and data

3.2.1 Study area

The 100 km² study area, in Bedfordshire, UK, (Figure 3-1) was chosen for its ease of access from Silsoe, the varying slopes and aspects, and the availability of a 1:25,000 scale soil map. It extends from OS grid reference (510000, 240000) in the south western corner to OS grid reference (520000, 250000) in the north eastern corner. It forms the northern edge of a sub-catchment to the river Ivel, the southern edge which is defined by an outcrop of the Lower Greensand running east of Haynes.

The main river in the area is the Ivel which runs south to north up the western edge, joining the Great Ouse about 3 km north of the area. The landscape is gently sloping and the dominant topographical feature is the chalky till plateau running from Haynes in the

South West to Mogerhanger in the North. This is at a maximum elevation of 90 m. The other significant topographic features are associated with outcrops of the Lower Greensand in the north east and around Old Warden. These range in elevation from 50 to 70 m and are the location of the field sites for this project. The superficial geology in the lower lying areas is Oxford, Ampthill and Gault Clays, Glacial Gravels and River Terraces. The drainage of the soils is governed by the underlying geology, and river network. Gley soils are prevalent along the course of the River Ivel, Brown sands are developed over the Lower Greensand. The soils and geology of this area are described in Wright (1987).

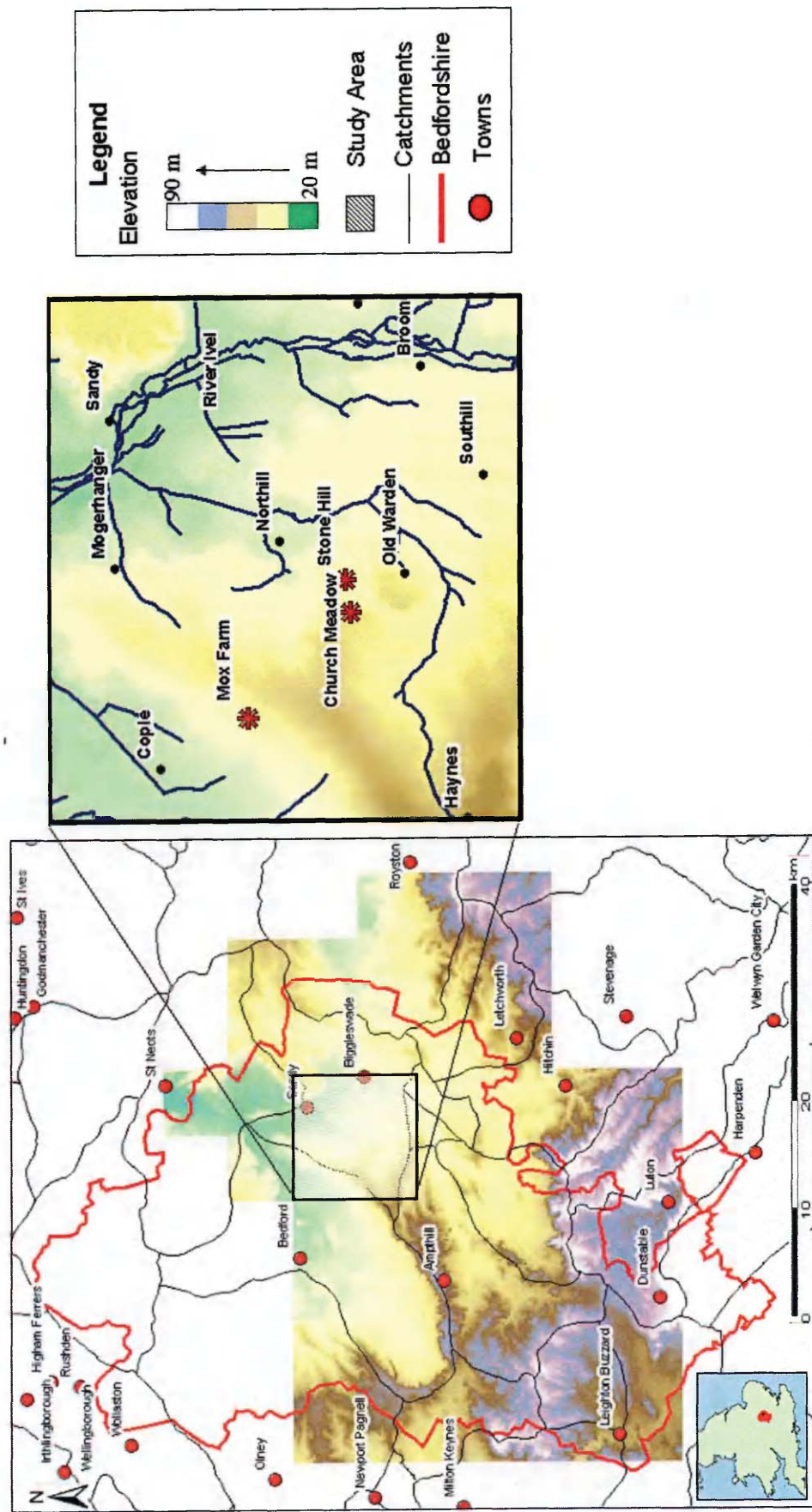


Figure 3-1 The Study area in Bedfordshire, UK. The elevation data are OS Land-Form PROFILE™ tiles (© Crown copyright Ordnance Survey All rights reserved) and the stream data are based on digital spatial data licensed from Centre for Ecology and Hydrology (© CEH(© crown copyright (0186A)). The detailed map shows the location of the three field sites at which soil moisture was measured (Stone Hill, Church Meadow and Mox Farm)

3.2.2 Field sites

Two fields, Stone Hill and Church Meadow (Figure 3-2), within a small sub-catchment were selected for the measurement of soil moisture. These sites were selected as part of the STAMINA project because they represented some of the maximum slopes in the area. The fields generally had moderate to strong slopes (4° - 11°) with small parts having moderately steep slopes up to 15° (Hodgson, 1976). The soils in the two fields were subsequently mapped at 1:10,000 scale by Rodney Burton in 2003. The field method for mapping can be found in Appendix III.



Figure 3-2 Photos showing the three field sites at which soil moisture was measured. (Top Left Stone Hill; Top Right, Church Meadow; Bottom, Mox Farm)

Stone Hill (7.8 ha) was part of the Shuttleworth estate and was managed for Shuttleworth Agricultural College by Guy Kiddy. It had a range of aspects from SE to SW, and the elevations ranged from 39 to 55 m. It contained more than 80% sandy soils (mapped at 1:10,000). The dominant soil series in each field was Maplestead a coarse loamy Argillic Brown Earth (Figure 3-3). The upper parts of Stone Hill are on the Lower Greensand and the base of the field is underlain by Ampthill Clay (Wright, 1987).

Church Meadow (7.4 ha) was also part of the Shuttleworth estate but farmed by Peter Allen. It had a range of aspects from NW to SE and the elevations ranged from 50m to

67m. This field site contained greater than 30% heavier clay soils. The dominant soil series was again Maplestead (Figure 3-3). Church Meadow is underlain by Till in the upper part and the Lower Greensand at the base of the field (Wright, 1987).

A third field in **Mox Farm (10 ha)** (Figure 3-2), was also used. This field was farmed by Paul Walsh. It was located on the other side of the ridge and drained into a different catchment. This field had N to NE facing slopes. The slopes were shallower than in Stone Hill and Church Meadow, generally between 3° and 6°. The elevations in Mox Farm range from 44 to 56 m. This field only had 1:25,000 soils data available. The three soil series mapped were heavy clays with increasing clay contents at depth (Figure 3-3). This field is underlain by glacial till (Wright, 1987).

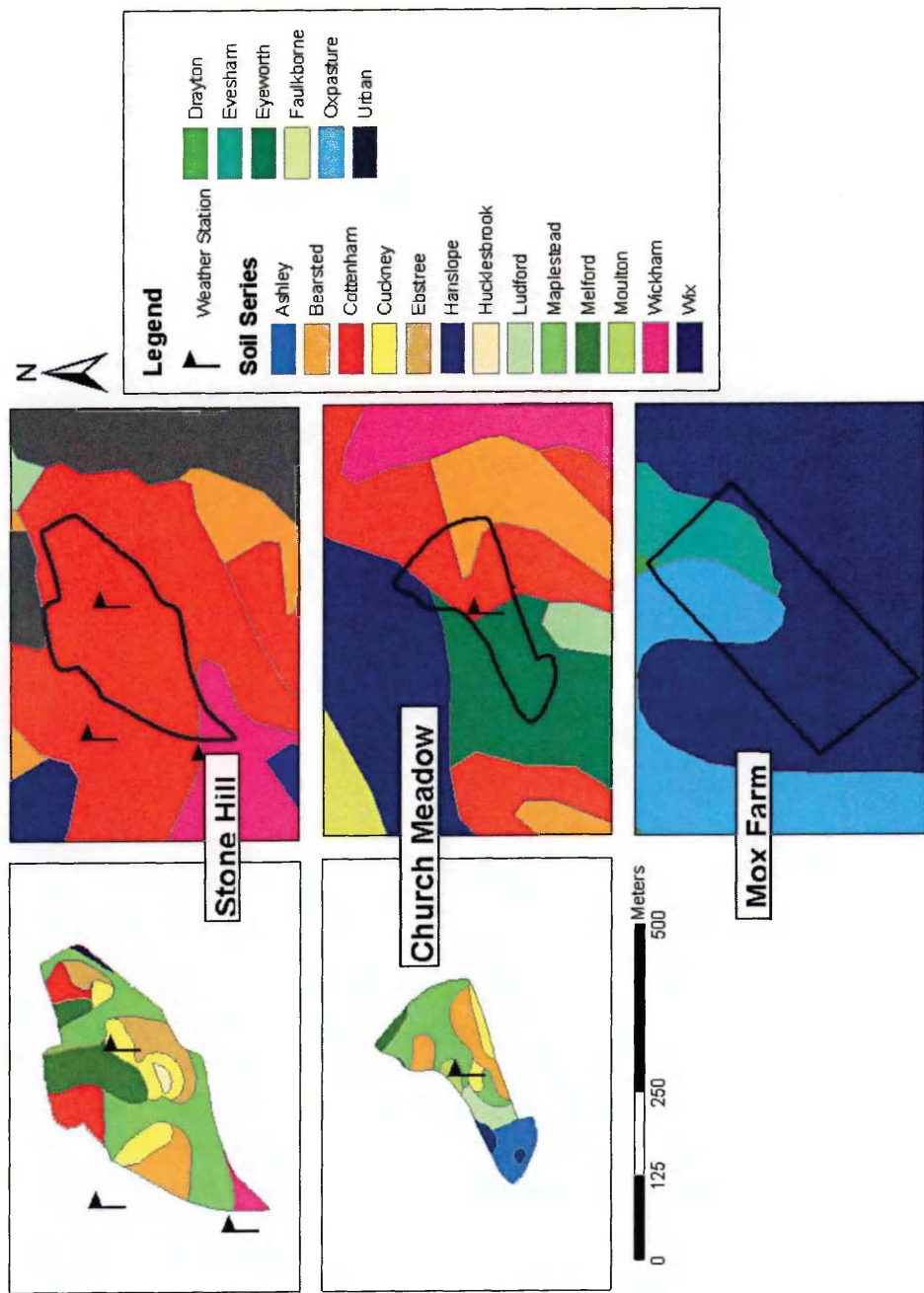


Figure 3-3 Soil maps for each of the three experimental fields in the study area. Left: Maps produced at 1:10,000 scale by (Burton, 2003), Right: Biggleswade Sheet TL14 at 1:25,000 scale (Wright, 1987)

Table 3-1 Soils descriptions for the soils in Stone Hill and Church Meadow at 1:10,000 scale (Soil Survey Bulletins)

Soil Series	Profile description	Substrate	Soil Water	Soil for Agriculture
Ashley (As) (Stagnogleyic argillic brown earth)	Stagnogleyic, sandy clay loam or clay loam to 600 mm overlying calcareous clay	Chalky till	Only occasionally water logged (Wetness Class II)	Moderate water availability. Only grass and potatoes will experience water stress in most years
Bearsted (BE) (Typical brown earth)	Sandy loam to 400-600 mm overlying brown sand	Lower Greensand	Well drained soils (Wetness Class I)	Moderate water availability. Crops will experience water stress in most years
Cottenham (cN) (Typical brown sand)	Sandy loam or loamy sand to 300 mm overlying iron rich sands	Lower Greensand	Well drained soils (Wetness Class I)	Low water availability. Most crops experience water stress in most years
Cuckney (CcK) (Typical brown sand)	Moderately deep sandy soils. Subsoils indicate seasonally effected by ground water	Lower Greensand	Well drained soils (Wetness Class I)	Slightly droughty for most arable crops
Ebstree (eS) (Argillic brown sand)	Argillic brown sands with Clay enriched laminations in deep subsoil	Drift over clay	Well drained soils (Wetness Class I)	Moderately droughty for cereals and Rape. Very droughty for sugar beet. Very droughty for potatoes and grass
Hanslope (Hn) (Typical calcareous pelosol)	Clay or clay loam over calcareous clay with chalk stones and mottles	Dense chalky clay	Slowly permeable, intermittently wet during winter/spring (Wetness Class II or III)	Moderate water availability for potatoes and grass. Spring working difficult (cereal land)
Hucklesbrook (HKB) (Typical argillic brown earth)	Stony sandy loam over Sandy clay loam	Lower Greensand	Well drained soils (Wetness Class I)	Moderately droughty for winter wheat. Very droughty for potatoes and grass

Soil Series	Profile description	Substrate	Soil Water	Soil for Agriculture
Ludford (LF) (Typical argillic brown earth)	Deep permeable soils Sandy loam- clay loam over sandy clay loam or clay loam	Sand or clay	Well drained soils (Wetness Class I)	Moderate water availability Droughty for potatoes and grass in average year
Maplested (MM) (Typical argillic brown earth)	Deep coarse loamy argillic brown earth	Lower Greensand	Well drained soils (Wetness Class I)	Slightly droughty for wheat/sugar beet and Oil Seed Rape. Moderately droughty for Potatoes Very droughty for grass
Melford (MJ) (Typical argillic brown earth)	Permeable soils clay loam over clay/ clay loam	Lower Greensand / Thin chalky till	Well drained soils (Wetness Class I)	Moderate soil water availability. Most crops slightly to moderately droughty
Moulton (Mo) (Typical argillic brown earth)	Deep sandy loam	Loamy sand	Well drained soils (Wetness Class I)	Slightly droughty for cereals /sugar beet and oil seed rape. Moderately droughty for potatoes Very droughty for grass
Wickham (Wh) Typical Stagnogley soil)	Medium loamy. Stagnogley soils	Clay from between 40 – 70 cm depth	Slowly permeable waterlogged most of the winter and early Spring (Wetness Class IV)	Require Autumn sown crops as Spring cultivation is limited
Wix (WC) (Gleyic argillic Brown Earth)	Gleyic Argillic Brown Earth	Drift over clay	Occasional water logging. Well drained soils. Waterlogged for various periods in the Winter due to underlying clay (Wetness Class II)	Slightly droughty for cereals /sugar beet and oil seed rape Very droughty for potatoes and grass

The following table (Table 3-2) outlines the cropping pattern in each of the fields in the three years in which sampling was carried out.

Table 3-2 Crop rotations in Stone Hill Church Meadow and Mox Farm over the soil moisture measurement campaigns

Field site	Growing Season	Crop
Church Meadow (7.4 ha)	2002-2003	Winter Wheat
	2003-2004	Oil Seed Rape (Oats were planned)
Stone Hill (7.8 ha)	2002-2003	Sugar Beat
	2003-2004	Winter Wheat
	2004-2005	Winter Wheat
Mox Farm (10 ha)	2004-2005	Spring Barley

3.3 Data available for analysis

Three key data sets available for this area are: elevation, soils and meteorological data. The following discussion outlines the specifications of these data sets and the way in which they were used in the project.

3.3.1 Digital Terrain Model

The elevation data obtained for this study were OS Land-Form PROFILE™ data with a 10 m grid spacing. These data were made available in 5 km² tiles in DXF format. These were converted into ESRI Grid files. The OS Land-Form PROFILE™ data is obtained from 5m interval contour data obtained from photogrametric mapping at 1:10,000 scale. Areas not visible on the original aerial photography were ground surveyed. This gives a vertical accuracy for the points of ± 2.5 m in this area (Land-Form PROFILE™ user guide).

3.3.2 Soil Maps and data

The soil data for this study came from two national databases held by NSRI. These were the Land Information System (LandIS) and National Soil Map (NATMAP):

- **LandIS** holds properties of individual soil series. These are in the form of representative profile descriptions for each soil series for different land uses;
- **NATMAP** is a vector map at **1:250,000** scale. The attributes for each polygon are the name of the soil association and the soil series which are included in the association in order of dominance at a national level (Figure 3-4).

Further, local soils data was also available. These were a **1:25,000** (Biggleswade Sheet TL14 (Wright, 1987)) of the 10 km² study area and **1:10,000** field survey maps were available from a survey by Burton (2003) (Figure 3-4). In order to obtain the data useful for analysis each of the three scales of soil maps were combined with the LANDIS data so that each polygon had the attributes of the soil series for arable land use (Table 3-1). The problem with the **1:250,000 scale map** was that the dominant series at a national level do not necessarily correspond to the series found in an area when mapped at a more detailed scale. This is shown in the analysis of soils mapped at 1:25,000 and present within each of the NATMAP polygons (Appendix IV).

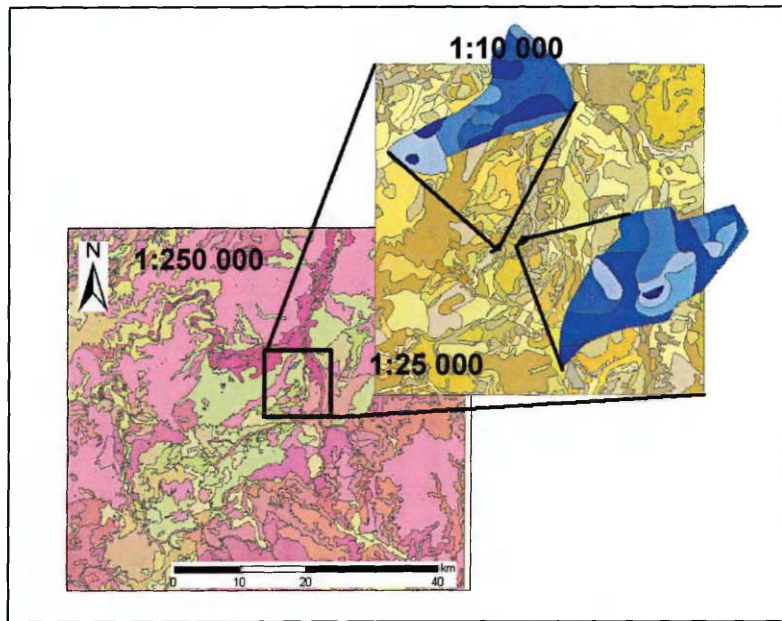


Figure 3-4 Available soil maps at increasingly detailed scales from 1:250,000 soil association maps to 1:25,000 and 1:10,000 scale soil series maps

In order to use this soils data in the STAMINA model a soil property database (Table 3-3) was put together, primarily using soils data from LANDIS. It was decided, by the STAMINA project team, that for the purpose of the STAMINA model the rooting depth and therefore the depth to which the modelling takes place is the base of the “B” Horizon. The “C” Horizon and Rock layers were not added to the database. Some of the soil series mapped were not found in LANDIS and information was added to the database from soil survey books and bulletins. These records did not have the required Van-Genuchten parameters, used in the soil hydrology part of the model to calculate water retention characteristics of the soil. These were calculated using pedo-

transfer functions (Mayr *et al.*, 1999), which required bulk density, organic carbon, sand, silt and clay as inputs.

Table 3-3 Description of the soil parameters required for running the STMINA model

Soil Property	Description
SERIES	Soil Series reference number
LAYER_NO	Layer number (1 is the upper most layer in the soil profile)
LOWER_DEPTH	Depth of the base of the layer below the ground surface (m)
SAND_TOTAL	Total sand content (%)
CLAY	Total clay content (%)
CARBON	Organic carbon (%)
BULK_DENSITY	Bulk density of the soil (kg m^{-3})
ALPHA n	Van-Genughten parameters
SWC_RES	Residual soil water content (Vol/Vol)

3.3.3 Weather data

Weather data was available from four standard Delta-T weather stations (Delta-T, 2004), installed as part of the STAMINA project (Figure 3-5). These stations were located in order to monitor the variation of meteorological variables within the topography represented in the Shuttleworth field sites.

Each weather station comprises a DL2e data logger with an LAC1 15 channel input card. The sensors fitted to each station are described in Table 3-4. To counter drift in the weather station clocks they were reset each time data was downloaded. To ensure that the clocks are set to an absolute reference the system clock, to which they are reset, is calibrated with the UK speaking clock.

The weather data required a significant amount of data processing to obtain both hourly and daily meteorological data sets. Missing data, due to equipment failure, from the base station had to be replaced by data from other stations in the catchment. This was not ideal as these data will be affected by topography. To minimise this effect data from the closest working meteorological station were used. A result of this was that it prevented the use of other stations for the comparison of the meteorological characteristics at different points in the landscape.

The data set from the station at the southern most point of Stone Hill (Figure 3-3) was used in the analysis in this thesis. The full range of measured parameters from this

station were used and input into the STAMINA model. The other 3 stations were maintained as part of the STAMINA project.

The data from two other permanent weather stations was used in extending the time series of data for the purpose of running the STAMINA model. These stations were located in Silsoe (OS Grid Ref: 508000, 235300) and Woburn (OS Grid Ref: 494500, 233500)



Figure 3-5 Delta-T weather station with wind vane, anemometer, net-radiometer, global radiation sensor, rain gauge, air temperature and relative humidity sensors

Table 3-4 Delta-T sensor descriptions and units of measurements (Delta-T, 2004)

Sensor Description	Units
Wind vane (WD4)	Compass degrees
Anemometer (AN4)	m.s-1
Global Radiation Sensor (ES2)	kW.h
Rain gauge (RG2)	mm
Air Temperature/Relative Humidity (RHT2nl)	°C / %
Net radiometer (NR2)*	mV

3.4 Measurement of soil moisture

There are several methods for determining the moisture content of soils as summarised in Lal and Shukla, (2004). The methods are divided into two groups. The following discussion outlines these methods and describes the Delta-T probes used in this study.

Direct methods

These involve removing soil samples from the ground and subsequent calculation of soil water content in the laboratory. The disadvantages of these methods are that they are destructive and time consuming, particularly if samples at depth are required. It is also not possible to monitor the same location on several sampling occasions. For these reasons direct methods are not appropriate for this study, which aims to monitor soil moisture at different depths over time.

Indirect methods

These include **Neutron Probes**, which measure the change in energy of neutrons emitted from a radioactive source. The thermalised neutrons which arrive back at the sensor are counted and related to the hydrogen and therefore water content in the soils. This method can be used with an access tube and is therefore non destructive. There are however health hazards and the method is expensive.

The other indirect methods that can be used to measure soil moisture both at depth and in the surface layer are based on measuring the dielectric properties of soils. There are two main methods The **first** is **Time Domain Reflectometry (TDR)**, where two metal rods are inserted into the ground and the average dielectric constant over the length of the rod is measured.

The **second** method is that based on the principles outlined in Gaskin and Miller, (1996). The principle of this instrument is that there is a transmission line with known impedance. The extension to this, the soil probe, has impedance based on the dielectric constant of the soil surrounding it (Figure 3-6). The difference in the impedance between these two sections of the probe causes a reflection back along the probe and a standing wave to be set up. The reflection co-efficient is a function of the difference of the impedance of the transmission line and that of the measurement probe. This can be calculated from knowing the amplitude difference between the transmitted and reflected waves. This is the method used in the Delta-T ML2 probes used to measure surface soil moisture for this thesis.

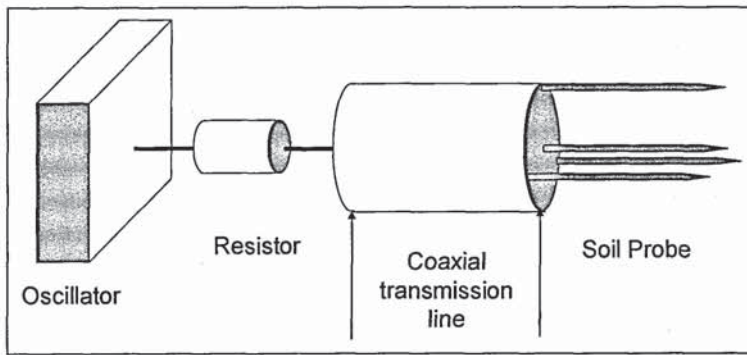


Figure 3-6 Diagrammatic representation of the MLURI soil moisture probe (From: Gaskin and Miller 1996)

A similar method is used in the Delta-T soil moisture profile tube probes. These generate a 100 MHz signal, which is applied to two stainless steel rings, generating an electromagnetic field (Figure 3-7). This is reflected back from the soil and the voltage of the resulting standing wave is measured (Delta-T Devices Ltd., 2001).

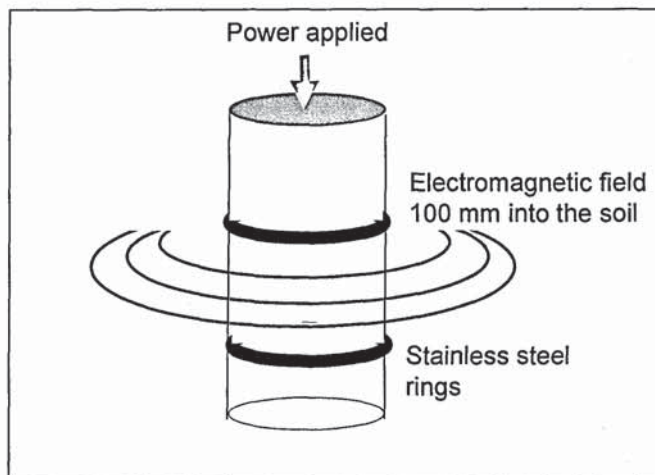


Figure 3-7 Principle of the Delta-T PR1 soil moisture probe (Delta-T Devices Ltd., 2001)

This method is preferred in this study as it is cheaper than the TDR method, measurements can be taken at varying depth below the surface and the equipment is highly portable and has small access tubes.

3.4.1 Surface soil moisture surveys

In 2004 three surface surveys were carried out in Stone Hill. A further five surveys were carried out in 2005, three in Church Meadow and two in Mox Farm (Table 3-4). Two further surveys were undertaken in Mox Farm, but these did not sample the whole field as they were interrupted by rain and the results are excluded from the analysis. The surveys were done on a 30 m paced grid, giving a minimum of 100

points (Figure 3-6). This grid was driven by the location of “tramlines” within the field in order to minimise damage to the standing crop, although measurements were taken from within the crops in order to prevent the results from bias due to soil compaction.

Table 3-5 Sampling dates and locations for the eight surface soil moisture surveys

Field site	Date
Stone Hill	7 th April 2004
	21 st May 2004
	13 th July 2004
Church Meadow	17 th June 2005
	1 st July 2005
	15 th July 2005
Mox Farm	10 th June 2005
	11 th July 2005

Soil moisture data was measured using a Delta-T, ML2 (Delta-T, 1999) sensor and moisture meter (Delta-T, HH2). This sensor uses the inductance method as outlined above (Gaskin and Miller, 1996). The monitoring probe collects soil moisture data from the top 100 mm of the soil. The location of each point was recorded using a Global Position System (GPS) device. The resident time at each location was 90 seconds and the positional precision less than 0.5 m in x and y (with z values approximately 50% worse). Sufficient carrier phase data was logged over the recording period for each point to be differentially corrected.

During the first survey it was noted that micro topography and local variations in crop growth may significantly influence the results. In order to account for these local variations four measurements were taken at each point, and the average was used for analysis. Four measurements at each point were sufficient as Analysis of Variance showed that there was greater variation across the field than at any given sampling location. At several sites in cracking clay soils inserting the probe without damaging it was difficult and resulted in less than four samples at these sites. The error in these measurements was $\pm 5\%$ vol/vol using the generic calibration of the instrument (Delta-T, 1999).

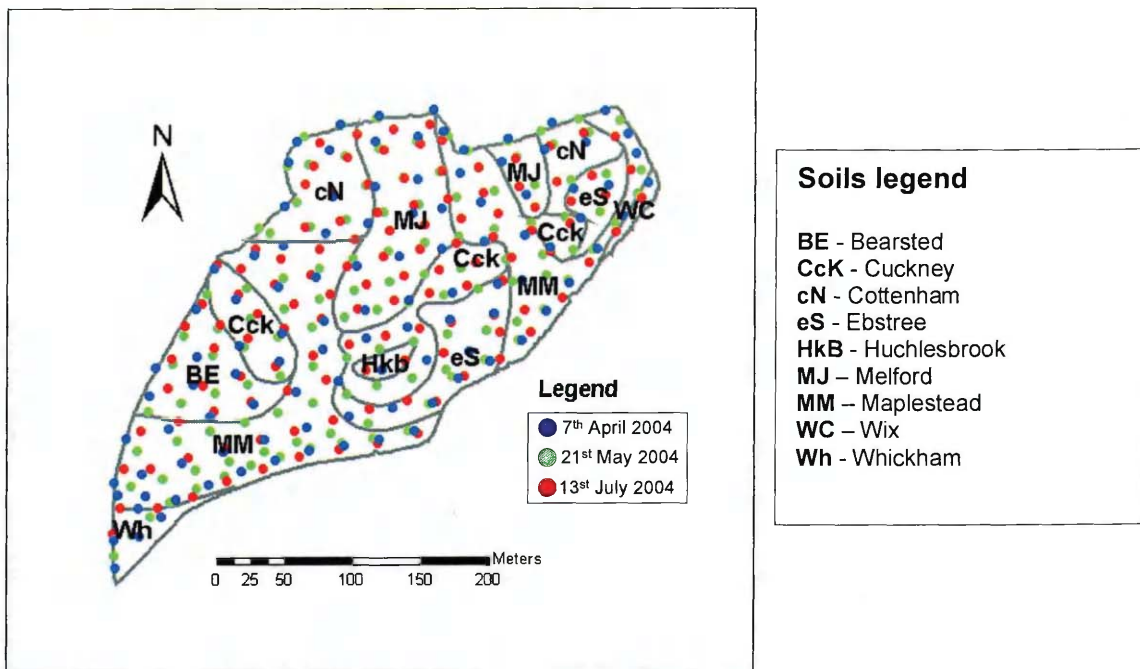


Figure 3-8 Layout of the field surveys in Stone Hill in 2004 for each of the three sampling dates, showing the soil boundaries at 1:10,000 scale (Burton , 2003) and the GPS locations of the sampling points

3.4.2 Soil moisture profile probe measurements

Soil moisture data was collected from the field sites in Stone Hill and Church Meadow using soil access tubes, in conjunction with a profile probe (Delta-T, PR1) (Delta-T, 2001) and moisture meter (Delta-T, HH2). This sensor uses the inductance method (Gaskin and Miller, 1996). The monitoring probe collects soil moisture data at six depths; 100, 200, 300, 400, 600 mm and 1 m. The access tubes were 28 mm in diameter and were inserted into a hole augured by a 25 mm diameter auger. This was done in an attempt to prevent the occurrence of air gaps down the length of the tube. These would introduce inaccuracies in the readings by preventing the propagation of the electromagnetic field, thus biasing the results. The tubes were installed with the top of the tube 5cm proud of the ground surface, this helps to prevent water from entering the tube. Additionally a rubber collar was fitted around the tube to prevent water from running down the side of the tube and a rubber cap prevents water from entering the tube itself. Figure 3-9 shows a soil access tube installed at site 1 in Church Meadow. The Delta-T equipment with generic calibration has an accuracy of $\pm 5\%$ vol/vol soil moisture (Delta-T, 2001).



Figure 3-9 Example of a Delta-T soil moisture Access Tube installed in Church Meadow showing the rubber cap and collar fitted in an attempt to prevent water entering the tube and bypass flow down the length of the tube.

Church Meadow (4.7 Ha), being the smaller of the two fields, contained 16 of the tubes and 22 were placed in Stone Hill (7.8 Ha) (Figure 3-10). Their locations were selected to give a wide range of topographic characteristics and to sample in as many of the soils, mapped at 1:10 000 scale as possible. The co-ordinates of the range of points were extracted in ArcGIS. They were located in the field using GPS with an accuracy of approximately 5m. Once all access tubes had been installed their actual position was recorded with differentially corrected GPS. The resident time at each location was 10 minutes using carrier phase signal giving a positional precision within 0.5 m in x, y (with z values approximately 50% worse). The 38 access tube sites were monitored from March to August 2003 and during the same period in 2004.

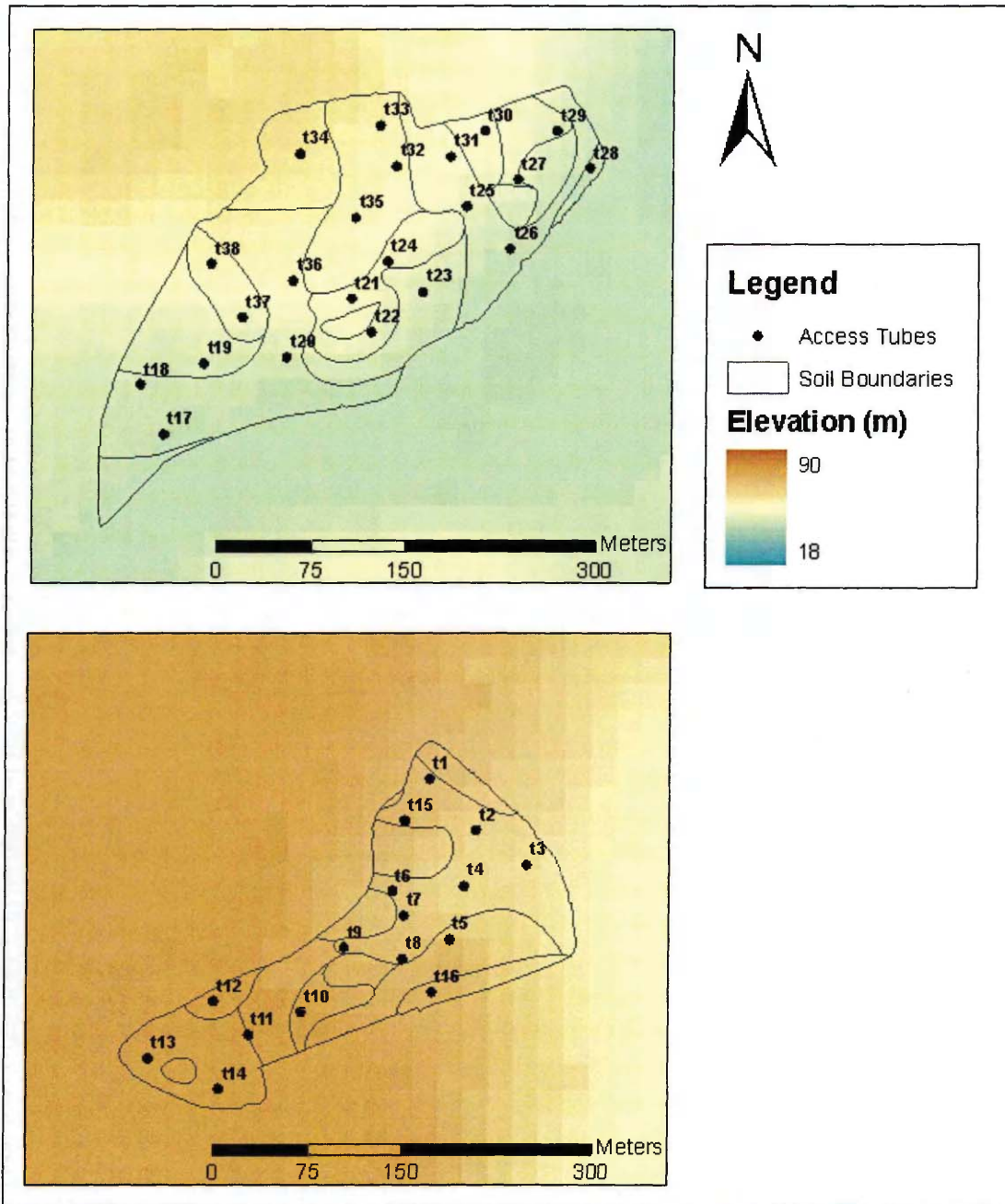


Figure 3-10 Locations of the 38 soil moisture access tubes installed in Stone Hill (22) (Top) and Church Meadow (16) (Bottom) The soil boundaries at 1:10,000 scale (Burton, 2003) are shown along with OS Land-Form PROFILE™ elevation data resampled to a 20 m grid

In the second year of the experiments six of the access tubes were not replaced, due to breakage during the removal of the tubes in 2003. The sites which were not sampled in 2004 were selected through analysis of the wetness index and soil type. The crop in Church Meadow in 2004 was Oil Seed Rape and as the crop developed it became impossible to reach the tubes. Sampling was eventually abandoned and none of the measurements from this field were used in the analysis.

3.5 DTM calculations

3.5.1 Introduction

Derivatives and indices derived from DTM data were required for both analysing the soil moisture measurements and running the physically based and index versions of the STAMINA model. The parameters calculated for the physically based model, using LandmapRTM (Macmillan *et al.*, 2000a), are outlined in section 1.3.2. The use of TAPES-G (Gallant and Wilson, 1996) and SRAD (Moore *et al.*, 1993) to calculate the topographic wetness indices and radiation indices respectively wetness is outlined in section 3.5.4.

The 10 m DTM derived from OS Land-Form PROFILETM elevation data was resampled in order to obtain the required grid sizes for modelling. TOPOGRID (Hutchinson, 1989) was used to achieve this with a cubic convolution interpolation. To run both TAPES-G (Gallant and Wilson, 1996) and LandMapRTM (Macmillan *et al.*, 2000a), the critical upslope area was required. This is the area at which overland flow paths become permanent streams. In order to determine the maximum grid size, at which major topographic features are lost from a DTM, the average hill slope length was calculated. The following discussion outlines the data processing required in order to calculate the critical upslope area and hill slope length from a DTM.

3.5.2 Calculation of critical upslope area

TOPAZ (Garbrecht and Martz, 1992) was used to calculate a critical upslope area grid from the 50 m DTM. (A 50 m grid size represented an appropriate compromise between the desired detail and the available Centre for Ecology and Hydrology (CEH) 1:50,000 river data). The value of each cell in the grid is the area of land from which from which water drains into that cell. This is known as the upslope area. This grid was classified using the following criteria:

- Any cell with an upslope area value greater than a chosen threshold area. These cells were given a value of one;
- Any cell with an upslope area value less than a chosen threshold area. These cells was classified as “No Data”.

Cells with a value of one represent permanent streams. This grid was then converted to a vector format, which showed the streams for a specified upslope area. The length of the calculated stream network was compared to the mapped (CEH) 1:50,000 river centre line data.(figure 3-11) This was repeated for various threshold values. The upslope area that gave the closest matching length of the CEH data was assumed to be the critical upslope area for the region (Table 3-5).

Table 3-6 Summary table showing a subset of the critical upslope areas and the corresponding length of the river network and how this differs from the length of the CEH river centre line data over the 100 km² study area

Upslope Area (ha)	Length of “Upslope Area” Rivers (km)	Difference between “Upslope Area” rivers and CEH rivers (km)
500	259	515
125	559	215
75	728	46
65	776	-3
63	789	-16
50	873	-100

This method of calculating a stream network does not produce braided streams. However the mapped CEH data contained a significant amount of braiding, particularly in the main river channel. The braiding was removed by eye from the CEH data before the analysis was carried out.

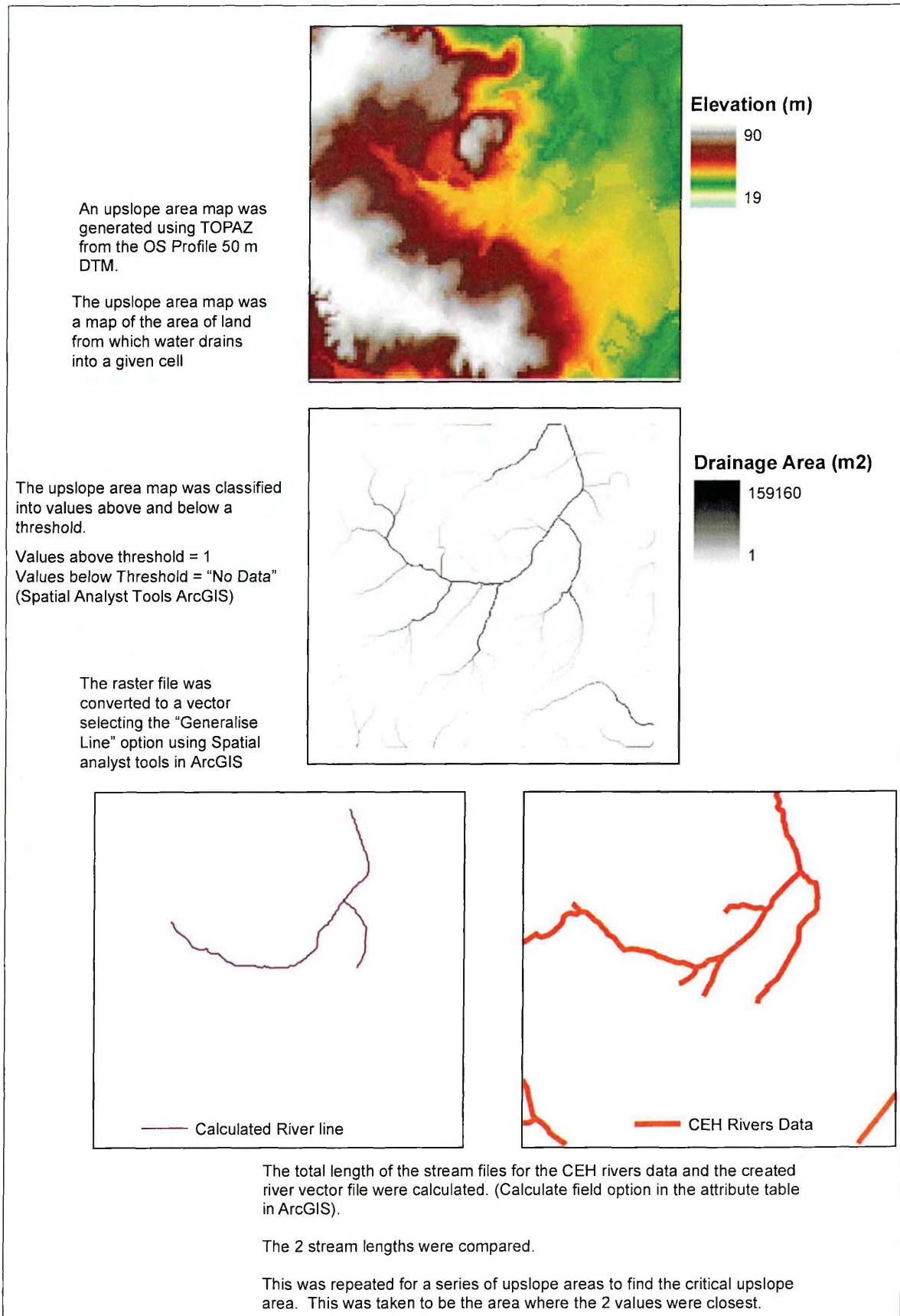


Figure 3-11 Description of the method used to calculate the critical upslope areas from the CEH 1:50,000 river data and the OS Land-Form PROFILE™ DTM

3.5.3 Calculation of drainage density

The drainage density (Equation 3-1) of the area was calculated using the CEH 1:50,000 data. This is defined by Horton (1945)

$$\text{DrainageDensity} = \frac{\text{Area}}{\text{DrainageLength}} \quad \text{Equation 3-1}$$

$$\text{HillSlopeLength} = \frac{1}{2} \text{DrainageDensity} \quad \text{Equation 3-2}$$

The study area has a half length (Equation 3-2) of 500 m. This is the absolute maximum grid size that can be used and still maintain the shape of the land with respect to the main drainage features. In practice this is much larger than the grid size at which the detail of the terrain is lost. The 500m grid size will lose any information on slope curvature which may point to flow convergence or divergence in the landscape. A further point that should be noted is the availability of the drainage data at 1: 50,000 scale. This data will not define the more minor streams that will play a part in dissecting the landscape and hence defining flow paths at a finer scale. These will be more apparent in a smaller gridded DTM.

3.5.4 The settings for use of TAPES-G/ DYNWET-G/SRAD

The wetness indices were calculated using DYNWET-G. The SSWI uses purely terrain attributes and is calculated from a depressionless DEM output from TOPOGRID, where each of the 'sinks' (cells at which flow paths terminate and there is no outlet) were filled. The critical upslope area was estimated to be 65,000 m² and the maximum cross grading area (upslope area above which flow paths are calculated using the D8 algorithm to prevent flow divergence in valley bottoms (Wilson and Gallant, 2000) was 100,000 m². The flow above this point is modelled using the multiple flow direction algorithm FD8 to minimise the occurrence of multiple parallel flow paths (Gallant and Wilson, 1996). The DEMON algorithm (Wilson and Gallant, 2000) is reported to give better estimates of the upslope area. However this cannot be used in DYNWET-G, so FD8 was used to maintain consistency between the attributes calculated in TAPES-G and DYNWET-G.

3.6 Method for the lysimeter experiments

Results from lysimeter experiments (Brown *et al.*, 1997) were used to test the drainage function in the soil hydrology module in the STAMINA model. This results of this investigation are documented in chapter 7. The method used in the lysimeter experiments is outlined below.

The lysimeters were planted with Winter Wheat sown on 11th October 1995 and harvested on 5th August 1996. The total average rainfall for the year prior to the experiment was very similar to the 25 year long term average. The temporal distribution of this rainfall was however different. There was a very dry spring (<50% long term average) and wet summer (>150% long term average). (Brown *et al.*, 1997)

Flow was collected from the base of the lysimeters, through a tipping 0.2 mm tipping rain gauge, at an hourly resolution (Brown *et al.*, 1997). The daily results were all that was available for the comparisons made in this study.

The STAMINA model simulated the period from 1st July 1995 to 1st November 1996. The input of hourly meteorological data was from a weather station on the lysimeter site and each of the lysimeters was treated as the reference point within the model.

4 Surface soil moisture surveys

4.1 Introduction

This chapter outlines the results from the surface soil moisture surveys. It addresses:

- The **meteorological variations** in the days and months leading up to the field surveys;
- The **temporal variations** in soil moisture and how these relate to the rainfall patterns;
- The **drivers of soil moisture**. This involves a comparison of the importance of soil classes and terrain variables for explaining the variation in soil moisture.

The question of how these results compare with published data is then addressed along with the implications of the results for the regional application of the STAMINA model.

4.2 Rainfall

Monthly rainfall data was compiled for the period March 2003 to September 2005 from the weather stations in the study area. Data from the Silsoe meteorological station was added for January and February 2003 and October to December 2005. This data was compared to the 30 year regional average from a combined data set for Woburn and Silsoe, Bedfordshire (Figure 4-1). The rainfall pattern for the years in which modelling and soil moisture measurements were carried out shows that:

- 2003 was significantly drier than the 30 year average, an annual rainfall of 455 mm compared to the 30 year average of 652 mm (Figure 4-1b);
- In 2003 Spring and late Summer were the driest periods with respect to the average rainfall (Figure 4-1a);
- In 2004 the annual rainfall was close to the 30 year average, at 602 mm (Figure 4-1b);

- In 2004 there was a very wet August, 223% of the average, and a dry September, 22% of the average (Figure 4-1a);
- 2005 was drier than the 30 year average, with the exception of the rainfall in June. The cumulative rainfall, however was greater than in 2003 (Figure 4-1a);
- If the exceptional rainfall in August 2004 is ignored all three years show cumulative rainfall below the 30 year average (Figure 4-1b).

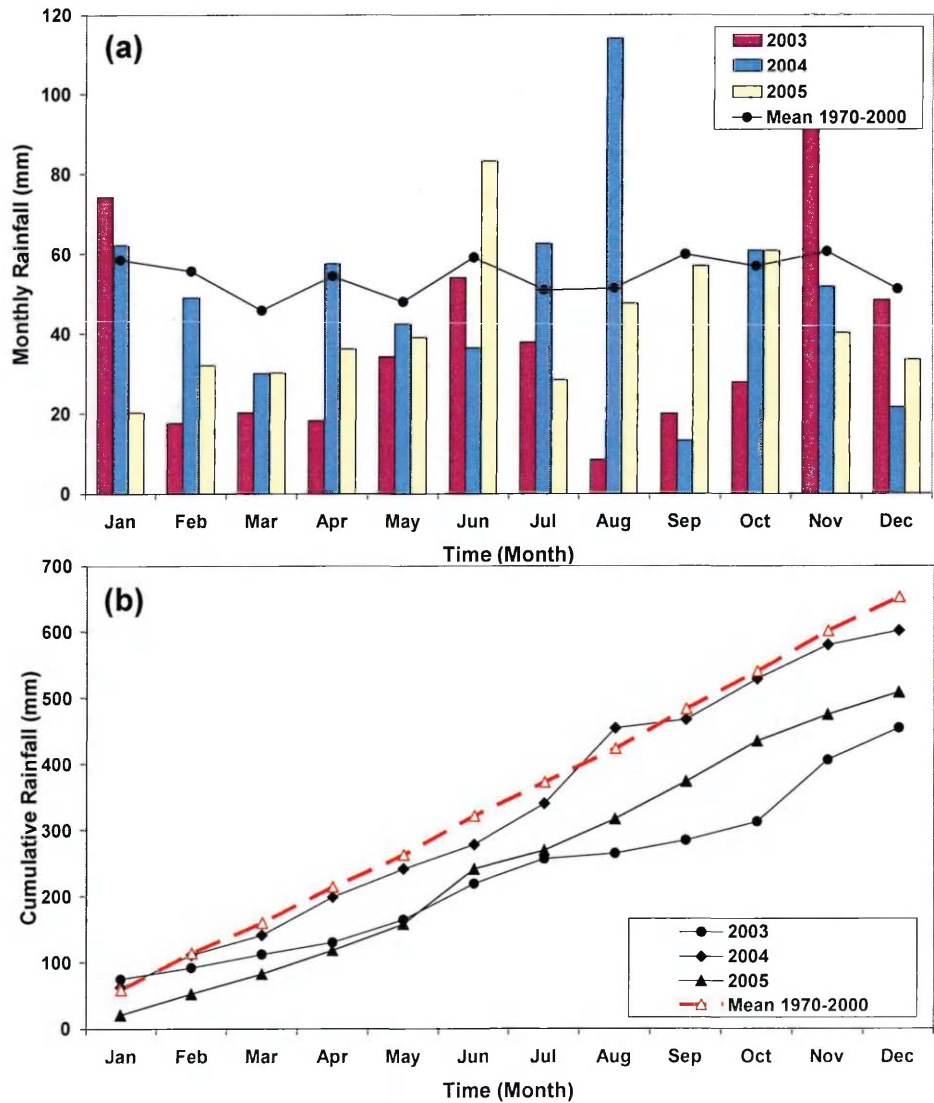


Figure 4-1 (a) Monthly rainfall data for 2003-2005 compared to the 30 year average (1970-2000) compiled from weather stations at Silsoe and Woburn, Bedfordshire **(b)** Cumulative monthly rainfall data for 2003-2005 compared to the 30 year average (1970-2000) compiled from weather stations at Silsoe and Woburn, Bedfordshire

4.3 Surface soil moisture analysis

The survey design and methods are outlined in Chapter 3. The results from the eight surface surveys which were completed are outlined in this chapter. These surveys were at:

- **Stone Hill:** 7th April, 21st May and 13th July 2004;
- **Church Meadow:** 17th June, 1st July and 15th July 2005;
- **Mox Farm:** 10th June and 11th July.

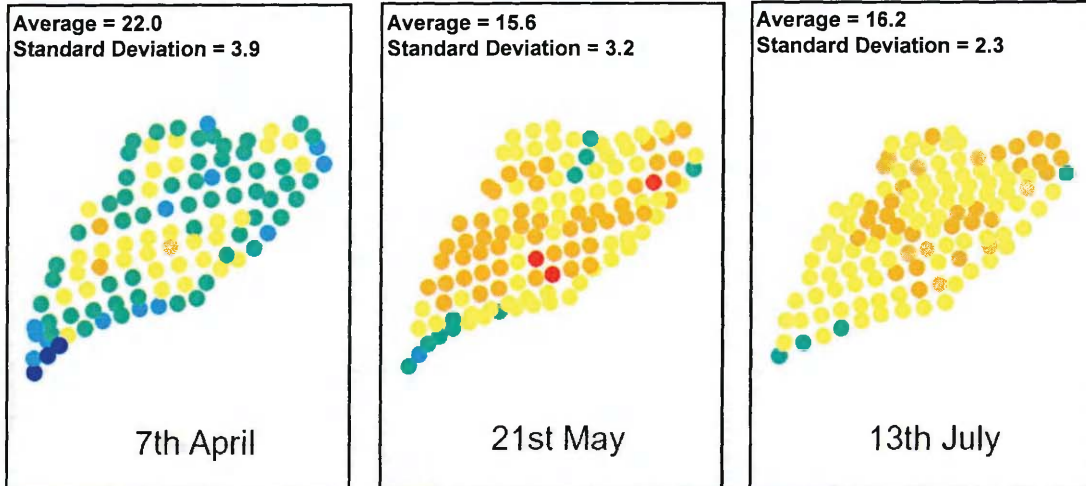
The soil moisture spatial patterns in each of the fields are shown in Figure 4-2 and the associated daily rainfall in Figure 4-3.

Several analyses were carried out separately on each field for each sampling date. These were:

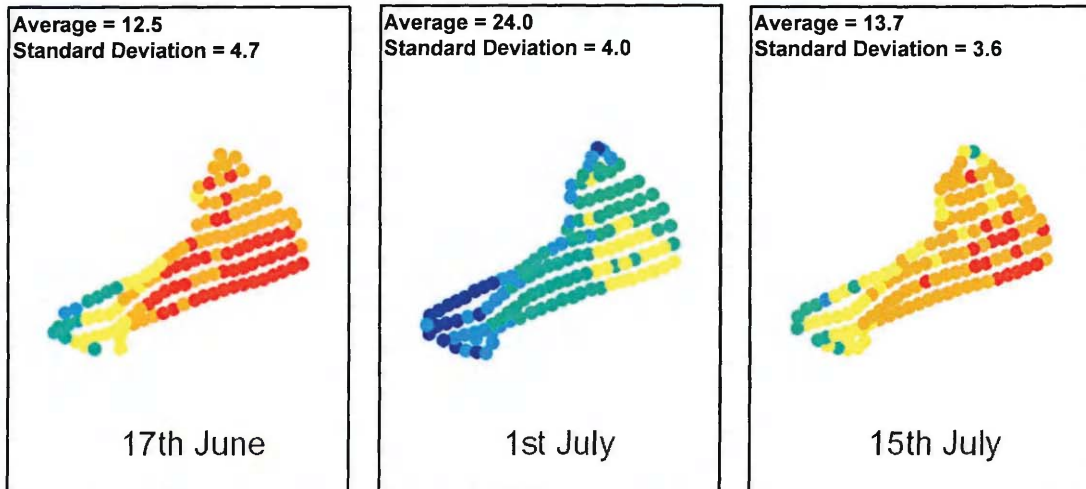
- A **visual assessment** of the spatial patterns of soil moisture and an **Analysis of Variance (ANOVA)** of the average soil moisture at each of the field sites with respect to sampling date. The aim of these analyses was to assess how the soil moisture conditions related to the rainfall data and which areas of the field appeared to have the highest and lowest soil moisture;
- An **ANOVA** of the soil moisture in each of the field sites with respect to soil series mapped at 1:10,000 scale and 1:25,000 scale. The aim of this analysis was to assess if a more detailed soil classification, with smaller taxonomic units was more effective at explaining the variation in soil moisture at each of the field sites and to gauge whether this changed over the growing season;
- The significant effects were then investigated using **Fisher Least Squares Difference (Fisher LSD)**. This showed homogeneous groups of soils, which display the same soil moisture characteristics. The aim of this analysis was to consider if soil series with similar physical characteristics displayed the same soil moisture patterns;

- A **Regression analysis** was then carried out on the soil moisture results with respect to the terrain variables calculated by TAPES-G and SRAD combined with soil series at 1:10,000 scale and 1:25,000 scale. The aim of this analysis was to examine how a combination of soils and terrain predict soil moisture and how the variation explained by adding terrain changed with the scale of the soil map.

Stone Hill 2004



Church Meadow 2005



Mox Farm 2005

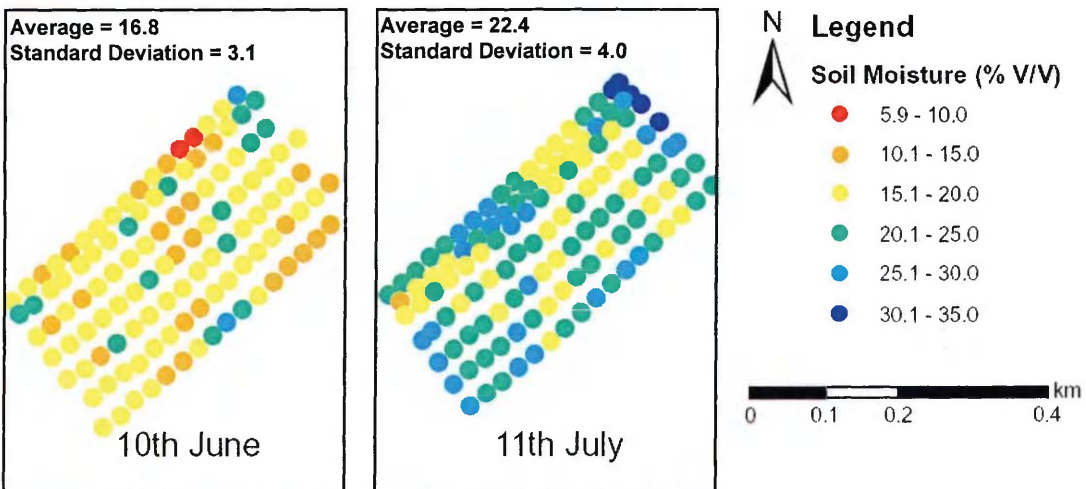


Figure 4-2 Surface soil moisture measurements (Top 100 mm) in Stone Hill, Church Meadow and Mox Farm. Taken using Delta-T ML2 ThetaProbe

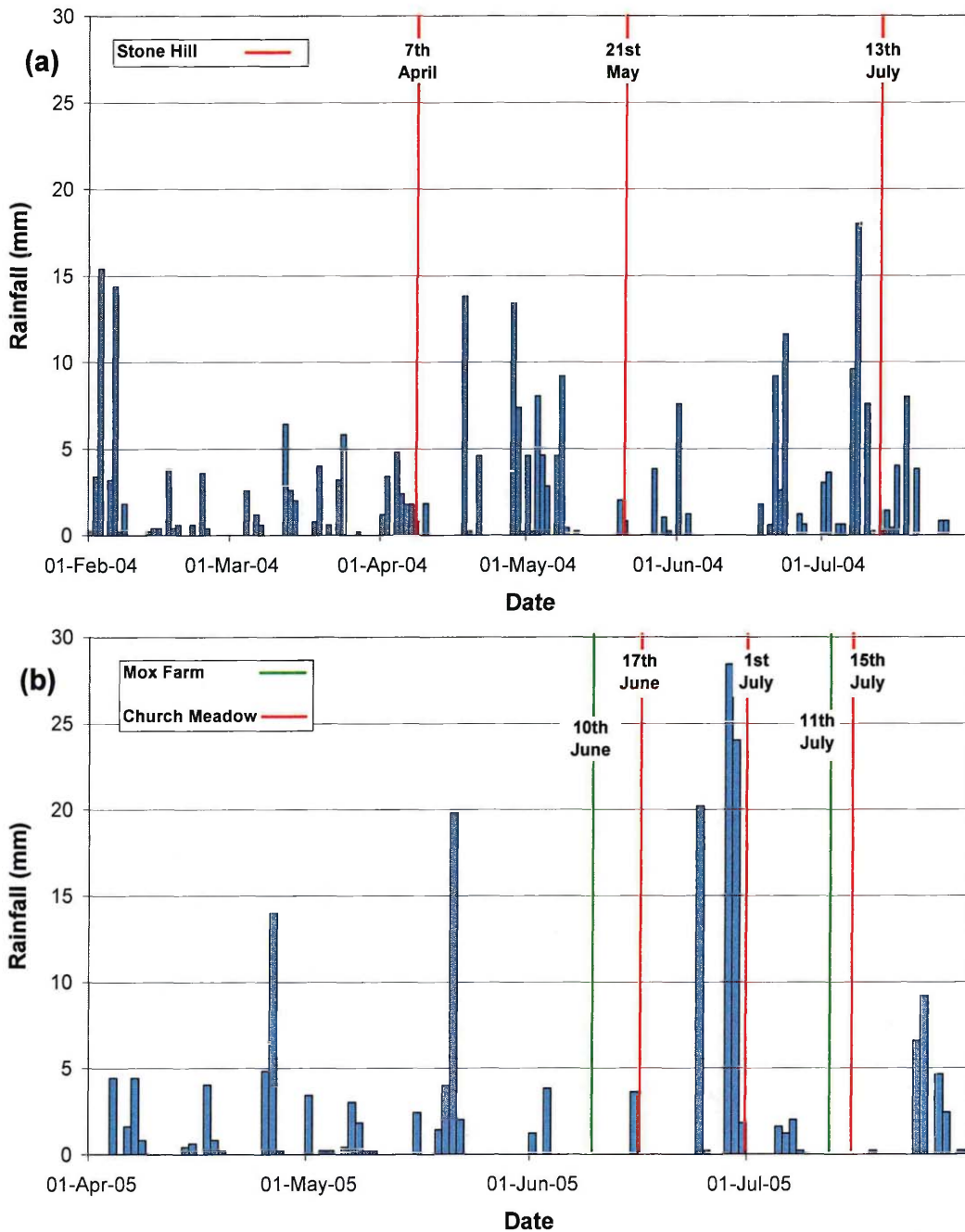


Figure 4-3 Daily rainfall data (Data from Stone Hill weather station) for the time periods prior to the surface soil moisture sampling. Vertical lines highlight the sampling dates in the relevant fields (a) 2004 (b) 2005

4.4 Temporal variation

4.4.1 Stone Hill - 2004

The soil moisture in Stone Hill (Figure 4-2) reflects the daily rainfall data for 2004 which shows a dry period, (2 mm rainfall in the previous 10 days) before the 21st May sampling date and increased rainfall (37 mm rainfall in the previous 10 days) before the 13th July sampling (Figure 4-3). The results from Stone Hill showed that it was significantly wetter on 7th April (14 mm rainfall in the previous 10 days) and after a wetter than average autumn and winter (Figure 4-1) than on the 21st May and 13th July, where it was not different (Figure 4-4). The spatial patterns appear to be quite stable in time, with the same areas of the field being wetter or drier at each sampling date. The wettest area at the southern most point of the field is associated with the poorly draining Wickham soil series (Table 3-1).

4.4.2 Church Meadow - 2005

Church Meadow was significantly wetter on the 1st July than on either the 17th June (4 mm rainfall in the previous 10 days) or the 15th July (5 mm rainfall in the previous 10 days) (Figure 4-4). This reflects the daily rainfall with 75 mm of rainfall (More than the monthly average) in the week prior to the 1st July (Figure 4-3). The spatial pattern, as in Stone Hill (Figure 4-2), appears stable in time. The wettest areas are in the flat area in the southern part of the field where the soils, Ashley and Hanslope, have a higher percentage clay content. The driest part of the field was again on the steepest slopes and also in the sandy series, Bearsted and Cuckney (Table 3-1)

4.4.3 Mox Farm - 2005

Soil moisture at Mox Farm (Figure 4-2) appeared to reflect the daily rainfall data (Figure 4-3). The field was significantly drier on the 10th June, immediately following a 20 day period, with only 7 mm of rainfall, than on the 11th July, a week after 75 mm rainfall fell in a week (Figure 4-4). The spatial pattern in Mox Farm showed that the driest area was associated with the lowest elevations, at the base of the dry valley. The wettest part was in the most northerly corner and was associated with the soil boundary between the Evesham, Oxpasture and Drayton soil series, mapped at 1:25,000 scale.

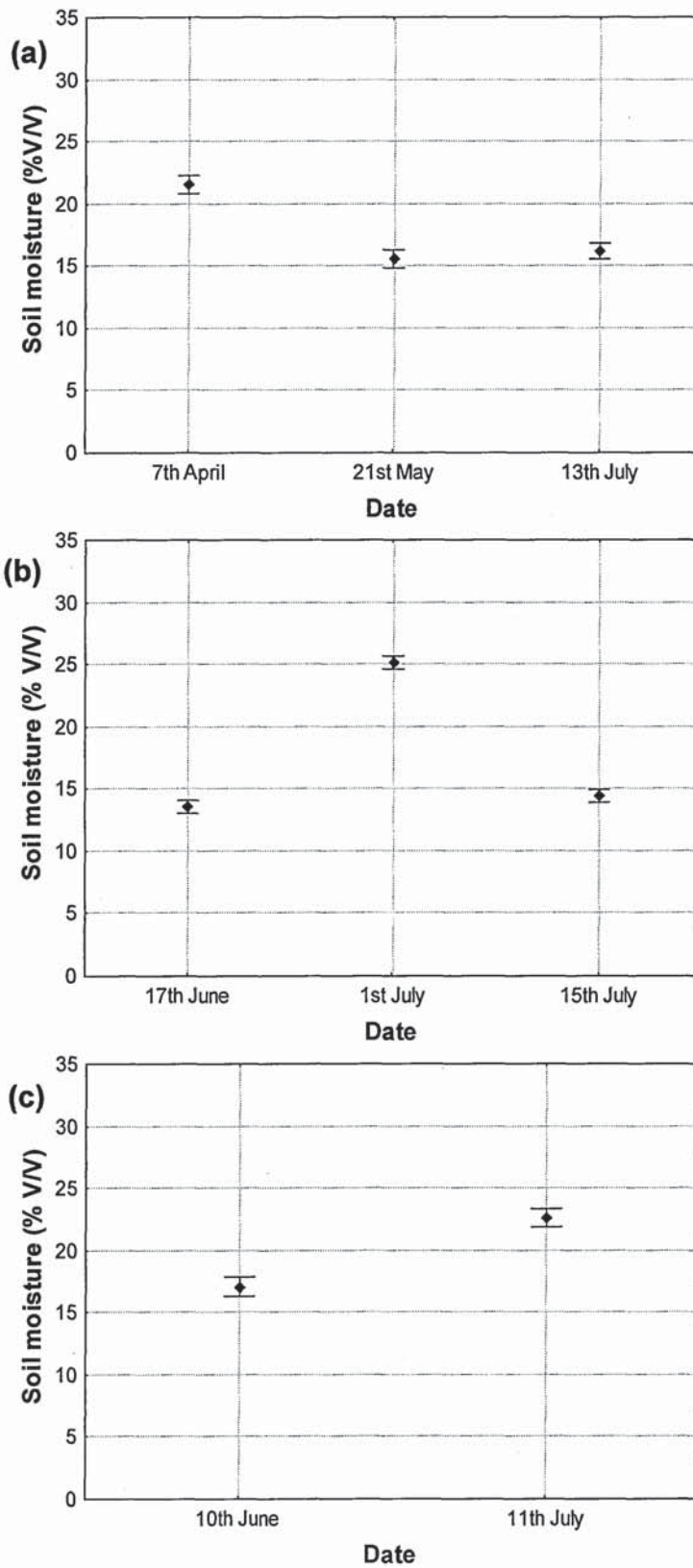


Figure 4-4 Results from ANOVA by sample date, bars show the 95% confidence intervals on the mean. (a) Stone Hill, 2004 (b) Church Meadow, 2005 (c) Mox Farm, 2005

4.5 Soil moisture variation with respect to soils

The results presented here are from an **ANOVA** carried out on the soil moisture field experiments with respect to:

- Soil series mapped at **1:25,000 scale** in Stone Hill, Church Meadow and Mox Farm (Biggleswade Sheet, TL14 (Wright, 1987));
- Soil series mapped at **1:10,000 scale**, in Stone Hill and Church Meadow (Burton, 2003).

4.5.1 Stone Hill- 2004

Stone Hill only has two soil series when mapped at 1:25,000 scale. The map picks out the Wickam series in the southern corner of the field, and the rest is mapped as the Cottenham series. The soils mapped at 1:25,000 explain 19% to 15% of the variation in soil moisture in the field. There was a decrease between April and July.

In Stone Hill the variance in soil moisture explained by taxonomic soil units at 1:10,000 scale decreases from 55% to 29% between April and July.

Investigating the significant soil series effect using **Fisher LSD** shows the soil series at 1:10,000 in Stone Hill fall into three groups, each having different soil moisture characteristics (Figure 4-5). These are:

- Wickham;
- Maplestead and Melford;
- Cottenham, Ebtree, Cuckney and Bearsted.

These groups correspond to soils with similar soil properties (Table 3-1). These groups can be distinguished in the moisture results for the 21st May and on the 7th April. On the 13th July the soils show more similarity in soil moisture, with Melford not being significantly different from Maplestead or Bearsted (Figure 4-5). These soil groups have similar properties. Maplestead and Melford are well drained permeable loamy soils over the Lower Greensand; Melford has a higher clay content. Wickham is a clay loam over clay and the others are freely draining sandy loams or loamy sands overlying the Lower Greensand.

4.5.2 Church Meadow-2005

There are four soil series in Church Meadow when mapped at 1:25,000 Hanslope, Eyeworth, Cottenham and Bearsted. The soils mapped at 1:25,000 explain 38% to 33% of the variation in soil moisture in the field, again there was a decrease between June and July.

In Church Meadow the variance explained by a taxonomic soil map at 1:10,000 scale decreases from 76% to 61% between June and July. Investigating the significant soil series effect using **Fisher LSD** shows three groups of soil series (Figure 4-5):

- Moulton, Ludford and Melford;
- Ashley and Hanslope;
- Cuckney and Bearsted.

These groups correspond to soils with similar soil properties (Table 3-1). Maplestead showed the same characteristics as Molton and Bearsted. These groups can be distinguished in the moisture results for the 15th July and on the 1st July, although on the 1st July. Maplestead was significantly drier than Moulton. On the 17th June Ashley was significantly drier than Hanslope and there was no significant difference between Molton and Melford. These soil groups have similar properties. Molton, Ludford and Melford are well drained soil permeable loamy soils over the Lower Greensand, Melford has a higher clay content. Ashley and Hanslope are a clay loam over clay and Cuckney and Bearsted are freely draining sandy loams or loamy sands overlying the Lower Greensand.

4.5.3 Mox Farm - 2005

The taxonomic soil units at 1:25,000 scale explain very little of the variation in the soil moisture measurements. On 10th June the variance explained was insignificant and on the 11th July only 4% of the variation was explained by soil series. Investigating the significant soil series effect using **Fisher LSD** showed that Evesham was significantly wetter than Oxpasture but neither are different to the Hanslope series. Mox Farm showed a significant difference in the average soil moisture conditions in the field between the 10th June and the 11th July, but no interaction between soil series and date of sampling.

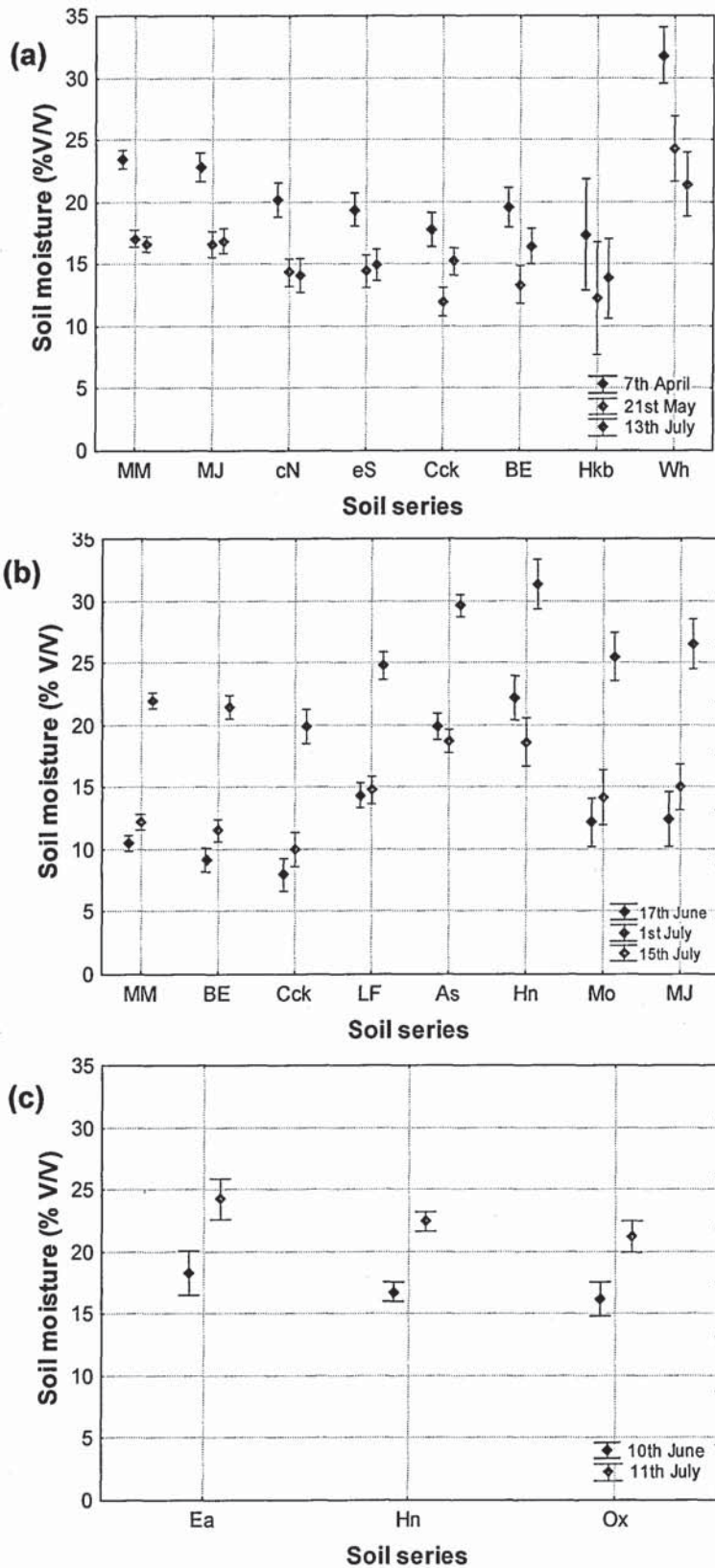


Figure 4-5 Results from ANOVA by soil series for each sampling date, bars show the 95% confidence intervals on the mean. **(a)** Stone Hill, 2004 **(b)** Church Meadow, 2005 **(c)** Mox Farm, 2005

4.6 Soil moisture variation with respect to topography

The results presented here are from the **Regression Analysis** carried out to compare the amount of variation explained by a combination of terrain variables

- Steady State Wetness Index (**SSWI**), the Quasi-Dynamic Wetness Index (**DYNWI**) calculated by DYNWET-G .(Figure 4-6);
- Short Wave Radiation on a Sloping Surface (Wm^{-2}) (**SWRSS**) calculated by SRAD (Figure 4-6).

A grid size of 50 m was used for each of these terrain variables. This grid size was selected because increasing the grid size from 20 m to 50 m generally increased the variance explained by the terrain attributes. Increasing the grid size to 100 m consistently decreased the variance explained by the terrain variables (Appendix V).

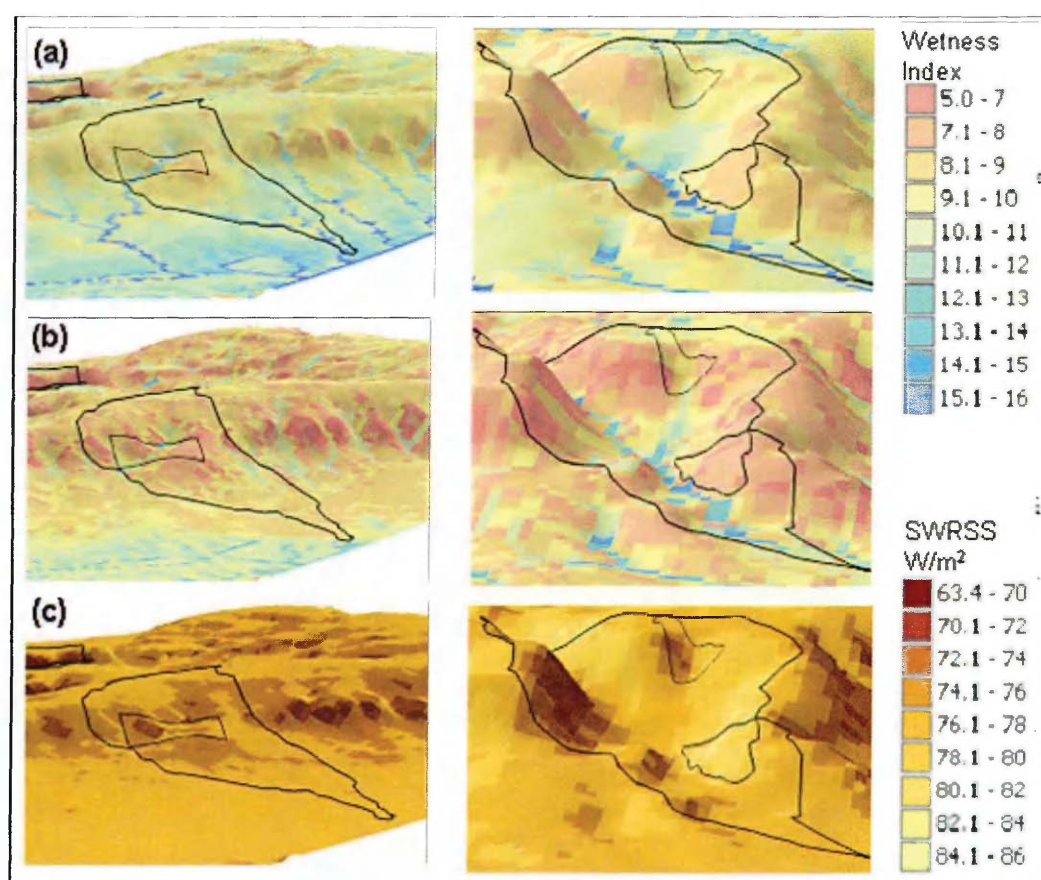


Figure 4-6 Indices in each of the three experimental fields (a) SSWI (b) DYNWI (c) SWRSS. The left 3 figures show the sub-catchment and field boundary of Mox Farm. The right 3 figures show the sub-catchment and field boundaries of Church Meadow at the top of the catchment and Stone Hill at the bottom of the catchment. (10*Vertical exaggeration)

Combining the soil moisture values with indices and taxonomic soil units for use in creating regression models was done by using GIS overlay and intersect tools within Hawth's Tools for ArcGIS (Figure 4-7).

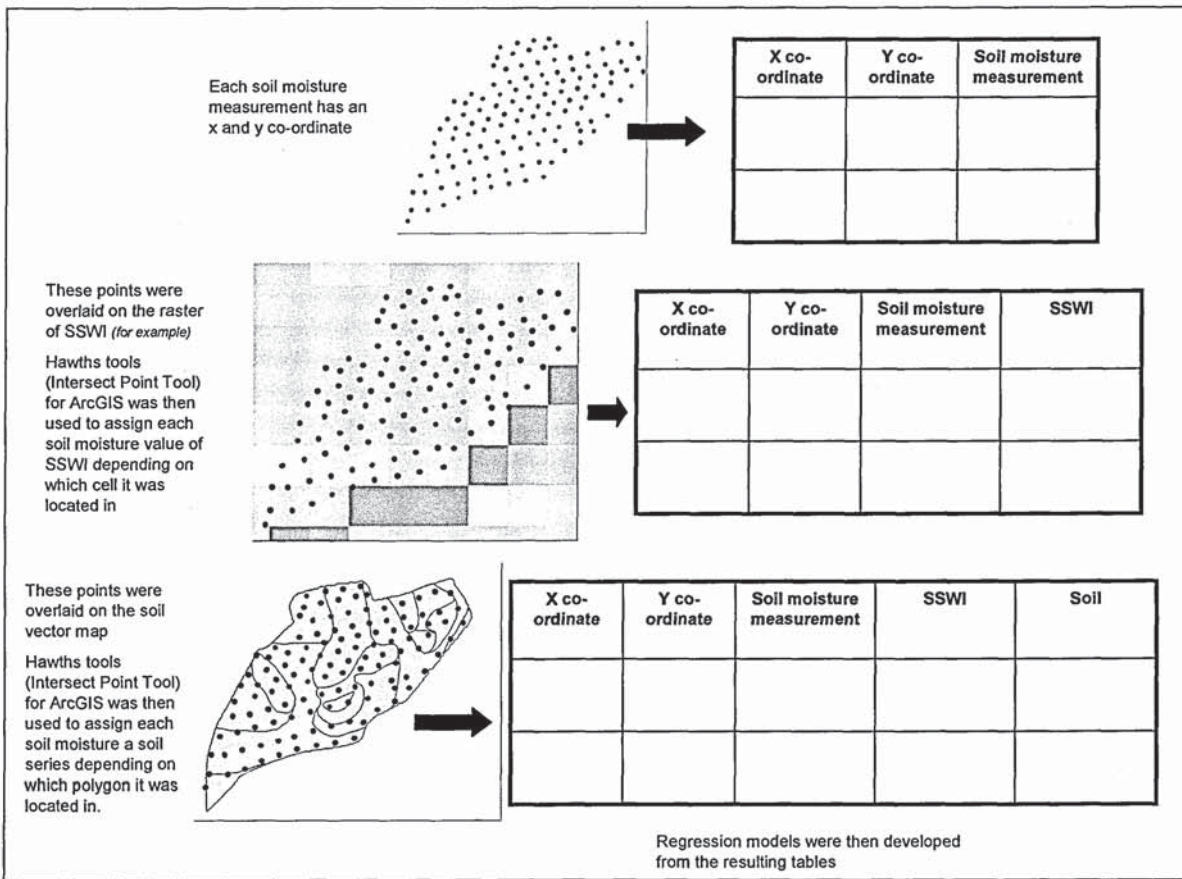


Figure 4-7 Description of the methods used to obtain the data required to generate regression models for analysing soil moisture distributions

4.6.1 Stone Hill-2004

The maximum amount of variance explained by terrain was in Stone Hill. The variance explained was at a maximum on the 21st May. Here the SSWI and SWRSS combined explain 44% of the variation in the soil moisture. Individually the SSWI explains 35% and SWRSS 31% (Figure 4-8). This implies that there was some interaction between these terrain variables, but also that some of the variation was explained uniquely by one or the other. This was also true on the 7th April. On the 13th July SWRSS was not significant when combined in a regression analysis with the SSWI. This implies that the variation explained by SWRSS was also explained by SSWI. The variation explained by terrain decreases on the 13th July (Figure 4-8) immediately after a prolonged period of rainfall (Figure 4-3). In Stone Hill the

DYNWI explains less or a similar proportion of the variation to the SSWI. The increased variation explained by the SSWI compared to the DYWI earlier in the year suggests that the area is tending towards a steady state situation, where a greater proportion of the upslope area is contributing to the soil moisture at a given location. This could be due to increased rainfall input over the winter and early spring and less vegetation cover meaning increased overland flow and a reduction in the interception rates.

4.6.2 Church Meadow-2005

The patterns in Church Meadow in 2005 were similar to those seen in Stone Hill in 2004. The DYNWI explains a similar proportion of the variation in soil moisture to the SSWI. The maximum variation explained by terrain was 32% on the 17th June (Figure 4-8). The variation explained by a combination of the SSWI and SWRSS decreases through the growing season, to 22% on the 15th July. On all three dates some of the variation was explained uniquely by either the SSWI or SWRSS.

4.6.3 Mox Farm-2005

The results from Mox Farm show that most of the time terrain does not explain a significant amount of the variation in soil moisture. When it was statistically significant the maximum variation explained was less than 10% (Figure 4-8)

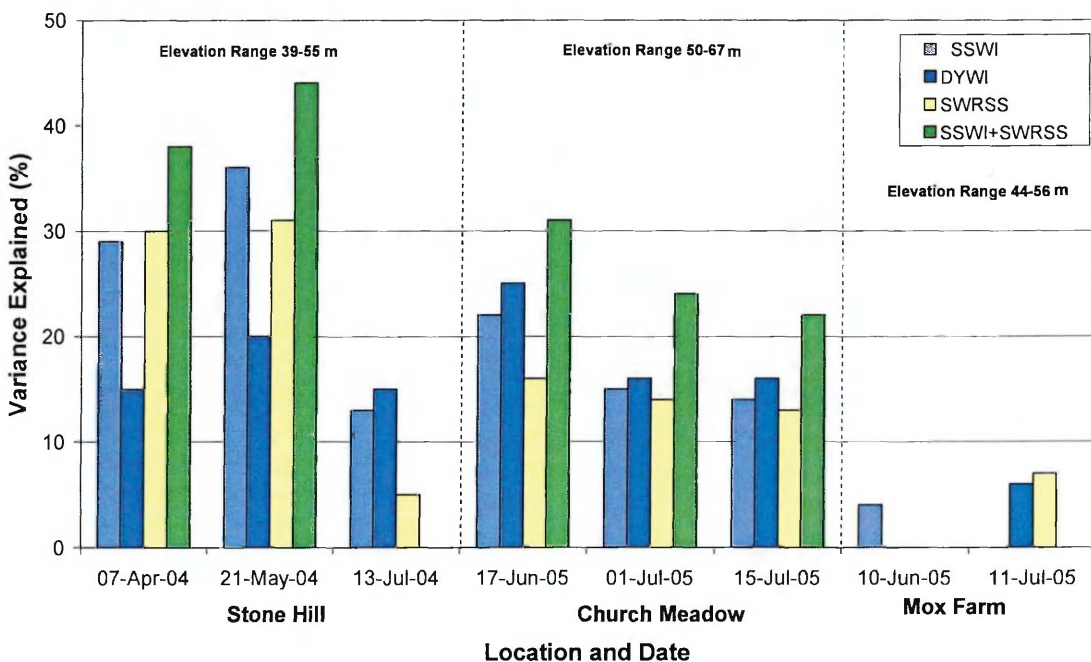


Figure 4-8 Variance in measured surface soil moisture explained by SSWI, DYNWI, SWRSS and SSWI+SWRSS for each of the eight soil moisture field surveys

4.7 Soil moisture with respect to terrain and soils combined

The results presented here are from the Regression Analysis produced to compare the amount of variation explained by a combination of the terrain indices as in section 4.6 and taxonomic soil groups as in section 4.5.

The results shown below are the most effective Regression Models for predicting soil moisture using both 1:10,000 and 1:25,000 soil maps with different combinations of the terrain indices SSWI and SWRSS. (Table 4-1). These regression models were obtained by modelling all combinations of soil, SSWI, SWRSS and then taking the models with the highest correlations (adjusted r^2 values) where all the variables in the model were statistically significant.

Table 4-1 Regression models explaining the largest proportion of variation in surface soil moisture for each of the eight sampling dates in Stone Hill, Church Meadow and Mox Farm. Model (i) Terrain + 1:10,000 soil data (ii) Terrain + 1:25,000 scale soil data (Figure 4-8 shows the variance in soil moisture explained by each of the models)

Field	Date	Regression Model
Stone Hill	7 th April 2004	(i) 1:10,000 soil + SWRSS (ii) SSWI + SWRSS
	21 st May 2004	(i) 1:10,000 soil + SSWI + SWRSS (ii) SSWI + SWRSS
	13 th July 2004	(i) 1:10,000 soil (ii) 1:25,000 soil + SSWI
Church Meadow	17 th June 2005	(i) 1:10,000 soil + SWRSS (ii) 1:25,000 soil + SSWI + SWRSS
	1 st July 2005	(i) 1:10,000 soil + SWRSS (ii) 1:25,000 soil + SSWI + SWRSS
	15 th July 2005	(i) 1:10,000 soil + SWRSS (ii) 1:25,000 soil + SSWI + SWRSS
Mox Farm	10 th June 2005	(ii) 1:25,000 soil + SSWI
	11 th July 2005	(ii) 1:25,000 soil + SSWI

4.7.1 Stone Hill-2004

Results from the analysis showed that the amount of variation in soil moisture explained by soils at 1:10,000 decreased from 55% to 33% over the growing season. Adding terrain to the Regression Models explained an additional 3% to 11% of the variance (Figure 4-9). This implies that variation explained by soils at 1:10,000 scale incorporates most of the variation explained by terrain indices. The variation explained by soils mapped at 1:25,000 was less than half the variation explained by the more detailed breakdown of soils in the landscape. The additional variation explained by terrain indices varies from 5% on the 13th July to 25% on the 21st May

(Figure 4-9). This again suggests an interaction between the variance explained by soils and that explained by terrain indices. The variation explained by soils at 1:25,000 scale and terrain indices was always less than the variation explained by soils alone at 1:10,000 scale. Adding 1:25,000 scale soil to the SSWI and SWRSS explains no more variation than the regression model using the two terrain indices (Table 4-1).

4.7.2 Church Meadow-2005

In Church Meadow the variation explained by soils at 1:10,000 was a maximum of 76% on the 17th June. This decreased to 61% by the 15th July. The increased variation explained by adding terrain indices was only 2% to 3% (Figure 4-8). This implies that soils mapped at 1:10,000 scale incorporate the variation in soil moisture explained by adding terrain indices. The results from adding terrain to the 1:25,000 soil data increase the variation explained by between 12% and 19% (Figure 4-9), showing that some of the variation explained by terrain was not picked up by the 1:25,000 soil map. Here the SSWI does not add any further information on soil moisture than the combined 1:10,000 scale soil data whereas it does add additional information to the 1:25,000 soils data.

4.7.3 Mox Farm-2005

A 1:10,000 scale soil map was not available for Mox Farm so analysis was carried out on the 1:25,000 soil map and the terrain variables. The proportion of variation explained by soils was less than 5% on the 11th July and not significant on the 10th June (Figure 4-8). Terrain indices and soils explain a maximum of 20% of the soil moisture variation on the 11th July (Figure 4-9). This suggests that soil and terrain indices are explaining different parts of the variation.

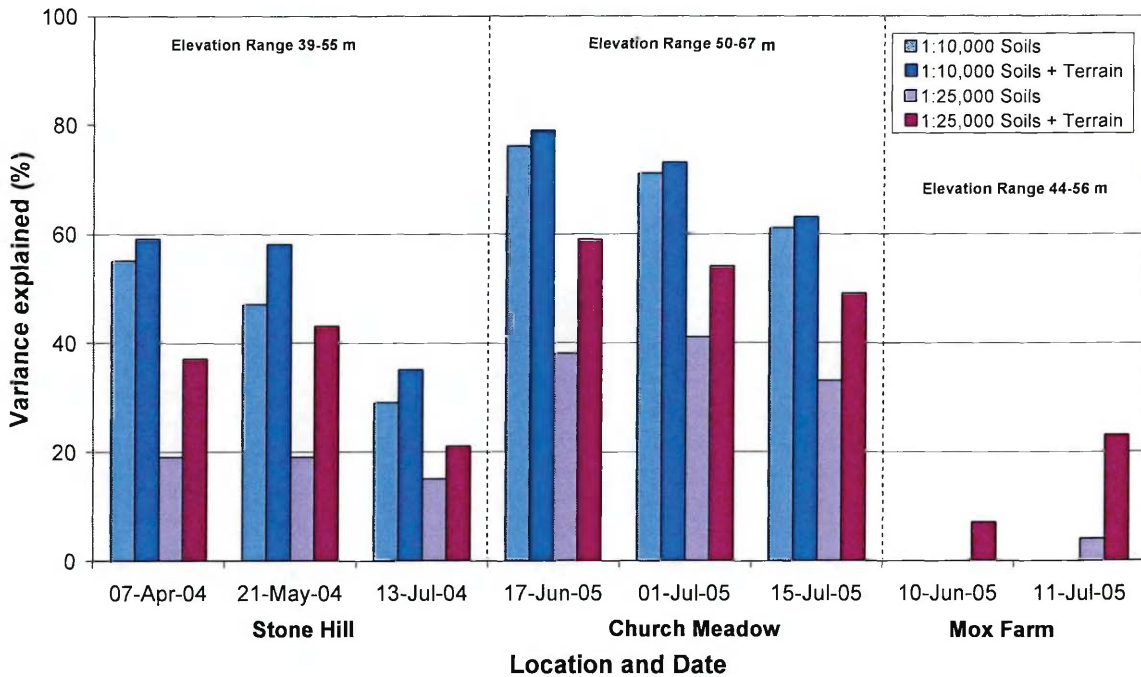


Figure 4-9 Variation in surface soil moisture explained by a combination of soils and Terrain indices for each of the eight sampling dates in Stone Hill, Church Meadow and Mox Farm. Variables included in the Soil + Terrain models can be found in Table 4-1

4.8 Discussion

4.8.1 Local soils and geology

The increasing proportion of variation in soil moisture explained by soils from Mox Farm to Stone Hill to Church Meadow could be linked to the underlying geology:

Stone Hill is mainly underlain by the Lower Greensand but part of the base of the field is over Ampthill Clay. This leads to the distinguishing of the Cottenham and Wickham soil series mapped at 1:25,000 scale. The lower Greensand is not homogeneous in space. For example there are lenses that have a higher clay content at the base of the profile. This leads to the distinguishing of the Maplestead and Melford series mapped at 1:10,000 scale. These soils, both sandy loams at the surface, did not show significant differences in soil moisture. The increased similarity between Maplestead, Bearsted and Melford immediately after heavy rainfall suggests also that soil properties become increasingly important as soils dry out, in particular for soils with similar surface soil properties.

The insignificance of 1:25,000 soils data when combined with terrain in the regression models for the 7th April and 21st May is thought to be due to the small amount of

variation in the soils at this scale. Furthermore the small area of the Wickham soil series is located at the lowest point of the field in the area with the highest wetness index values.

Church Meadow overlays, in similar proportions, the Lower Greensand and Till. These two underlying geologies have significantly different drainage regimes and also overlying soil series. There appears to be a greater change in the depth to the Lower Greensand than in Stone Hill. This was highlighted as this area was mapped as two soil series (Bearstead and Cottenham), distinguished by this factor, at 1:25,000 scale. These factors suggest that a larger amount of the variation in soil moisture should be explained by the variation in soil series.

This factor is seen in the results in this field, although terrain is less important for predicting the variation in Church Meadow than in Stone Hill. One reason for this could be that the Church Meadow sampling dates are much later in the growing season than the first two sampling dates in Stone Hill and therefore there will be increased crop cover masking the differences due to terrain. (Cantón *et al.*, 2004, Kang *et al.*, 2000, Western *et al.*, 2002). This could be due to increased interception leading to a smaller percentage of rainfall arriving at the soil surface and restricted overland flow.

Mox Farm is underlain purely by Till. This is reflected in the overlying soil series. The three series mapped at 1:25,000 are all a combination of clays and clay loams. They all have similar drainage characteristics, only varying slightly in their depth to clay (Oxpasture and Evesham), or structure (Hanslope). This could explain why soils are not significant in explaining the soil moisture characteristics in Mox Farm.

A major factor in the very small amount of variance in soil moisture explained by a combination of terrain and soils in Mox Farm could be the much shallower slopes in the field compared to Stone Hill and Church Meadow. The results showed, as expected, that increased slopes lead to an increase in the proportion of soil moisture being explained by terrain.

4.8.2 Controls on surface soil moisture

Western *et al.* (2004) showed correlation lengths in soil moisture between 30 m and 300 m for the catchments they studied. This was supported by geostatistical studies

they found in the literature which suggested correlation lengths between 50 m and 200 m at a small catchment scale. The results outlined in this chapter showed that soils data at a detailed, 1:10,000 scale explain the patterns in soil moisture better than the 1:25,000 scale soil mapping units. It is suggested that detailed scale soil data could go some way to represent the short correlation lengths seen in previous studies since soil polygons at this scale have dimensions in the range 30m to 300m. These correlation lengths are generally much smaller than the sizes of the polygons in 1:25,000 maps. Lin *et al.*, (2006a) have also suggested that Order I (1:15,840) soils data available in the USA is important in understanding site specific applications such as precision farming and hill slope hydrology. The findings here support this view and the concept of the emerging field of Hydropedology.

The results presented in this chapter reflected the periodicity of rainfall events and dry spells, as suggested by Parent *et al.*, (2006) and Lauzon *et al.*, (2004). This relationship could be further explored by more frequent sampling in the different soil series within the fields and then comparing the power spectrum of rainfall data and soil moisture data (Lauzon *et al.*, 2004, Parent *et al.*, 2006,). This type of analysis would give an insight into the response in different soils and from an agricultural perspective could lead to quantitative assessment on the need for irrigation and the trafficability of the soil after rainfall.

The general stability with respect to soil series and terrain was consistent with the spatial organisation of soil moisture reported in the literature. In this study the maximum variation in surface soil moisture explained by terrain variables was 44%. This compares with a maximum value reported by Western *et al.* (2004) of 51% from previous literature and 60% in their own studies.

The proportion of variance explained by soils and terrain decreases over the growing season. The reason for this is thought to be that topographic and soil effects are becoming masked by increasing vegetation cover (Kang *et al.*, 2000, Western *et al.*, 2002, Cantón *et al.*, 2004). This may also mask any effects of changing processes from horizontal soil movement to vertical as suggested by several authors (Western *et al.*, 1999, Peters-Lidard *et al.*, 2001, Aryal *et al.*, 2003, Pelenq, 2003). The results of this study are only from the growing season and to investigate this change fully a bare ground plot in each of the soils would need to be sampled throughout the whole year.

In this study the built in calibration between measured voltage and soil moisture was used. This lead to measurement errors of up to $\pm 5\%$ vol/vol (Delta-T, 1999). Each field and date combination was analysed individually with respect to soil and terrain. This will reduce the effects of instrument drift, as the interest of this study was relative values. The effects of errors in the location of the points will be minimal as the error in locating each sample was significantly less than the 50 m grid size used for the analysis of terrain effects. Errors in the measurement locations with respect to the soil boundaries may have some effect on the results, but the boundaries only represent the best estimate of the division in gradually changing soil properties.

4.9 Major Results

The key results and conclusions from the surface soil moisture measurements are:

- SWRSS and SSWI together explain more variation in soil moisture than either individually, which suggests that the two indices may be reflecting different processes;
- Percentage of variation explained increases when the grid size increases from 20 m to 50 m. It is suggested that at 20 m there was too much detail in the terrain indices and the soil moisture reflects the more general trends. Further investigation could be carried out by smoothing the 20 m DTM;
- The variance explained purely by terrain was consistent with results from other studies. (Western *et al.*, 2004);
- Detailed soil information aids the prediction of soil moisture. This has been suggested in other studies but soils data have often not been available at a detailed enough scale to quantify the effects (Wilson *et al.*, 2005, Lin *et al.*, 2006);
- In the absence of this data, terrain data combined with lower resolution soil data gives better results than terrain data alone. This study has used data mapped to soil series level. Further investigation is needed to address the question of how effective adding terrain to soil association data would be;
- The controls on soil moisture are shown here to be a complex interaction of soils, terrain and underlying geology.

4.9.1 Implications for the STAMINA model

The STAMINA model requires an index with which to distribute rainfall. These results suggest that of the two indices discussed here the SSWI is sufficient as it has similar, and in many cases better correlation with soil moisture than the more complex DYNWI. The SSWI is however much simpler to calculate and only requires a DTM and not soils data. It is therefore only dependant on the scale of the available terrain data and not the more limited availability of soils data.

The indices do not explain all of the soil moisture variation in the landscape but in the model the vertical redistribution of water, and hence the soil effect, is part of the model structure.

5 Soil moisture access tube results

5.1 Introduction

This chapter outlines the results from the soil moisture profile measurements. It addresses:

- The **meteorological conditions** throughout the measurement campaign;
- How the **spatial patterns** of soil moisture change with time and depth;
- The **drivers of soil moisture**. This involves a comparison of the importance of soil series, soil texture at the point of the observation and depth for explaining the variation in soil moisture.

The question of how these results compare with published data is then addressed along with the implications of the results for the STAMINA model.

5.2 Access tubes

Soil moisture was sampled in Church Meadow and Stone Hill at 38 locations over two growing seasons. The tubes were removed for harvest and subsequent tillage after the 2003 growing seasons. They were replaced, in 2004, after the tramlines had been established in the spring. The 38 access tubes in Stone Hill (22) and Church Meadow (16) sampled soil moisture at six depths from 100 mm to 1 m in a broad range of landscape positions and soil series as mapped at 1:10,000 scale (Figure 5-1). Full details of the methods can be found in Section 3.5. Details of the field management can be found in Table 3-2.

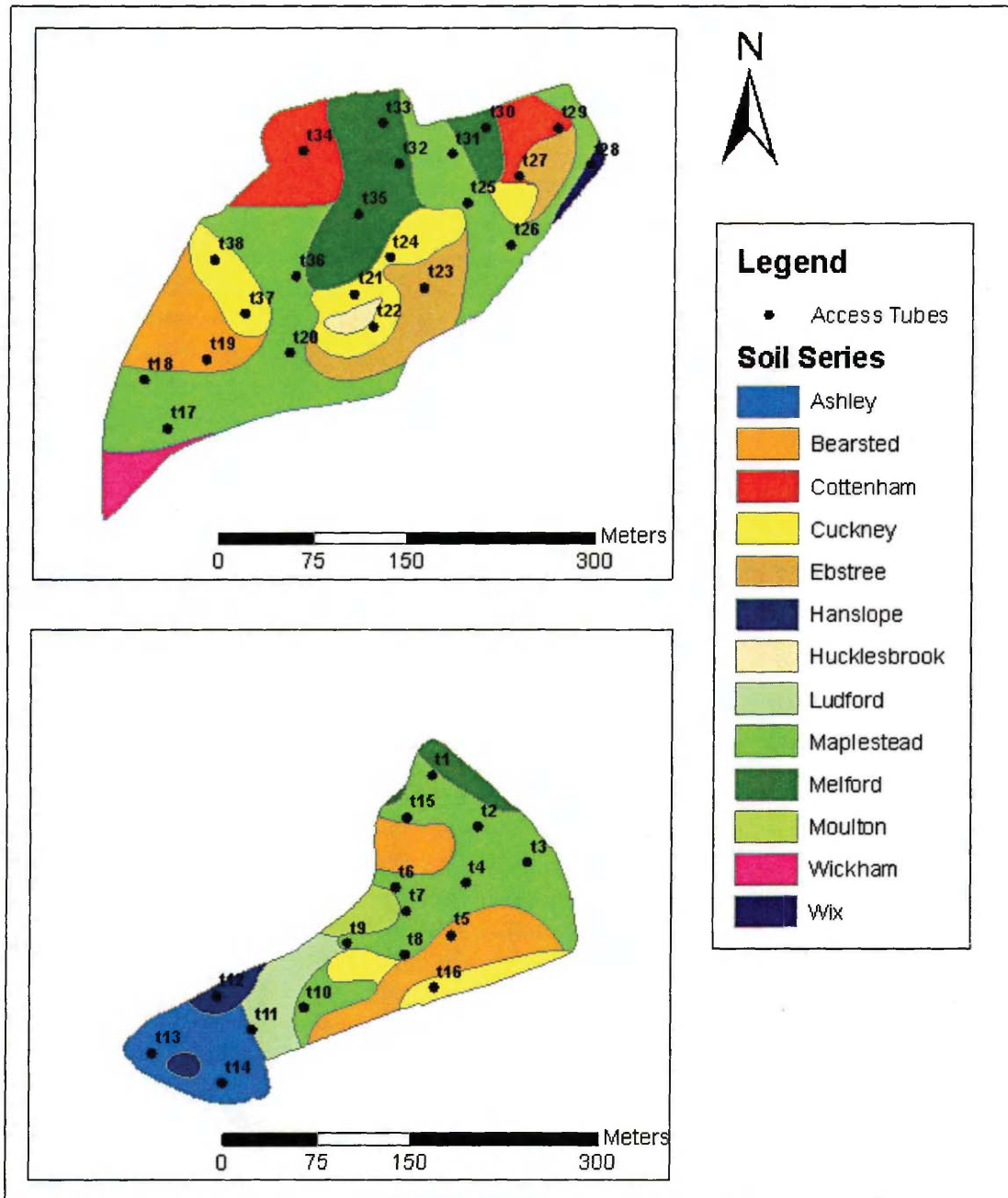


Figure 5-1 Locations of the 38 soil moisture Access tubes in Stone Hill (Top) Church Meadow (Bottom) Access tube numbers are those referred to in the text. The background map is the 10:,000 scale soil map for each of the fields.

Analysis was carried out on the results from Stone Hill in 2003 and 2004 and Church Meadow for 2003 alone. A number of tubes were excluded from the analysis for a variety of reasons, as specified in Table 5-1.

Table 5-1 Access tube measurement locations excluded from analysis. Figure 5-1 shows location of the points in the field.

Field location	Dates	Tubes	Tubes excluded	Reason
Stone Hill	29 th Apr 2003 – 8 th Sept 2003	17-38	30	Lid removed early in the season allowing water to enter the tube
Stone Hill	8 th Apr 2004 – 6 th Aug 2004	17-38	18, 22, 35	Several tubes were broken on removal in 2003.
Stone Hill	8 th Apr 2004 – 6 th Aug 2004	17-38	24	Loose in ground leading to poor contact. Most readings below the range of the instrument
Church Meadow	1 st Apr 2004 – 23 rd Jul 2003	1-16	None	N/A
Church Meadow	2004	Sampling abandoned		Field inaccessible due to growth of Oil Seed Rape

5.2.1 Measurement errors

Very high and low values were recorded at certain tubes in the two years of this experiment. It is suggested that these values may be associated with:

- High in situ soil moisture values that are outside the calibration range of the instrument (5% – 60%), where its response becomes non linear (Delta-T, 2001) or bypass flow causing water to accumulate in air gaps down the tube;
- Low in situ soil moisture values that are outside the calibration range of the instrument (5% – 60%), where its response becomes non linear (Delta-T) or air gaps caused by the sand caving in when it is augured to place the tube.

The extreme soil moisture values in the observations from Stone Hill and Church Meadow were often directly related to the soil profile descriptions.

Low readings, often below the range of the instrument, are found at Stone Hill tubes 21, 22, 24 and 38 in 2003 and in the same horizons at 21 and 38 in 2004. These are in sand layers below less sandy layers (Example Figure 5-2).

In Church Meadow tubes 5 and 8 have very low readings and readings below the range of the instrument at 600 mm and 300 mm respectively. These results, as for those in Stone Hill in 2003 and 2004 are associated with freely draining sandy soils.

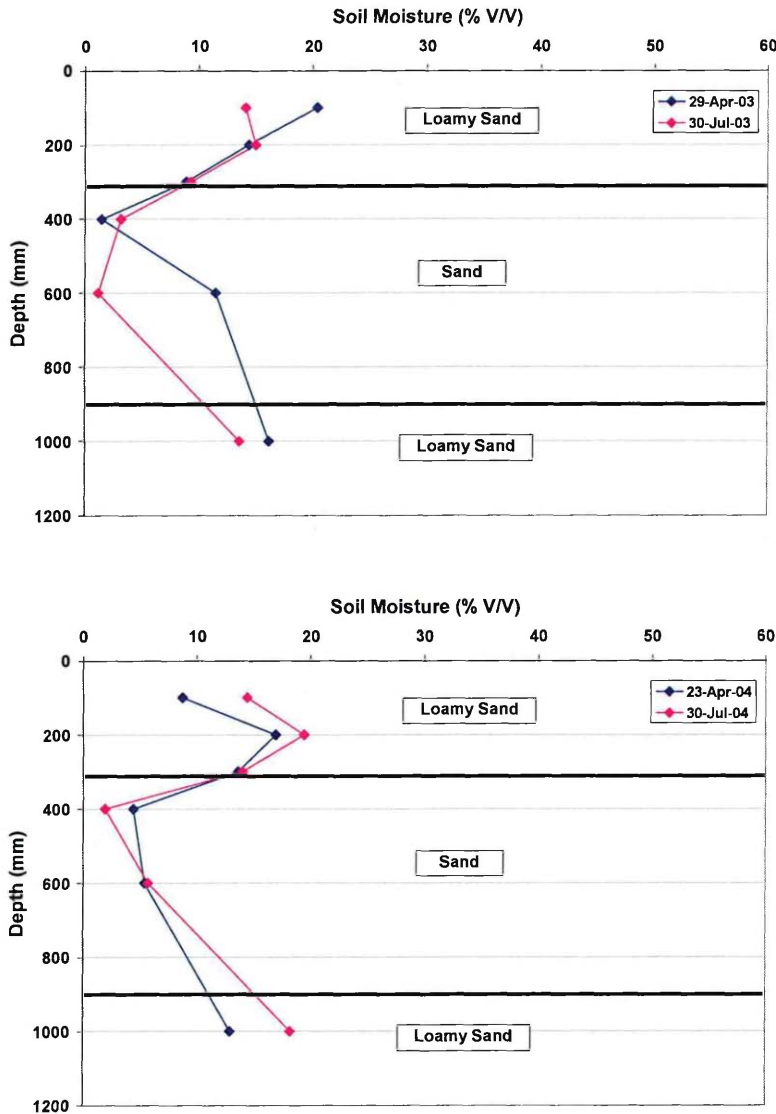


Figure 5-2 Results from soil moisture access tube measurements (Tube 21) for the beginning and end of the season in (a) 2003 and (b) 2004

Soil moisture values greater than 60% are recorded at 1 m at tubes 17, 26, 33 and 36 in 2003 and 2004 and also at tube 23 in 2004. In 17 and 36 these high values are associated with gleyed horizons in the soil profile. In 23, 26 and 33 they are associated with slowly permeable clay rich horizons.

The measurements from tubes 12, 13 and 14 show very high soil moisture, recorded values up to 90% vol/vol, at the lower depths in the tubes. These values are associated with gleyed, clay texture, horizons in the soil (Figure 5-3).

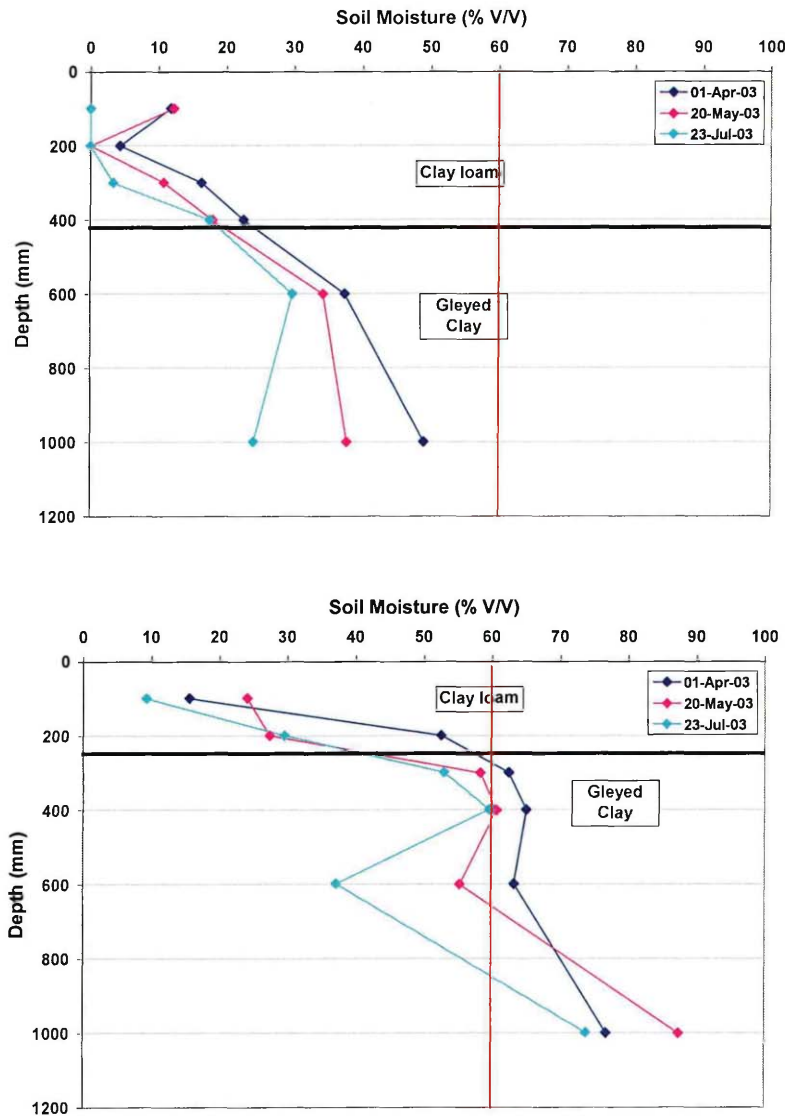


Figure 5-3 Results from soil moisture access tube measurements (a) Tube 12 (b) Tube 13 in 2003 (The red line shows approximate saturated water content)

5.2.2 Discussion

Measurements of soil moisture above 60% vol/vol are unlikely in these soils as this is in excess of their total porosity. Measurements above this level were not excluded from the analysis, as the aim of the research was to look for spatial patterns in the landscape and therefore the **relative** patterns of the measurements. The results outlined above show that these extreme values appear to be related to real soil

phenomena. The values below 5% vol/vol are generally lower than the wilting point of the soils but were not excluded for the same reason. It should also be noted that the errors in these measurements may be greater than the stated precision of the instrument ($\pm 5\%$ vol/vol) due to the non linear response of the instrument at high and low soil moisture values. The tubes with obvious installation problems had already been excluded from the analysis (Table 5-1). Further investigation into how extreme values are interpreted and how they affect the conclusions drawn is required. Crave and Gascuel-Oudoux, (1997) capped values above 80% vol/vol at 80% vol/vol as a solution to this problem. The difference in their work was that the results are gravimetric water contents measured in the laboratory and hence extreme values can be associated with observed phenomena

5.3 Weather conditions

The weather data for the measurement period are shown below for ease of interpretation for the soil moisture results that follow (Figure 5-4). The context of the weather, with respect to the long term average, can be found in Section 4.2. The weather conditions in 2003 and 2004 are very different. It can be seen from Figure 5-2 that 2003 is much hotter and drier than 2004. It is likely that the soil moisture conditions reflect this difference. The high rainfall in August 2004 may be expected to cause some soil moisture recharge. Rainfall in the Summer, Autumn and Winter of 2002, however, were above the long term average and wetter than in 2003 (Met Office, 2006)

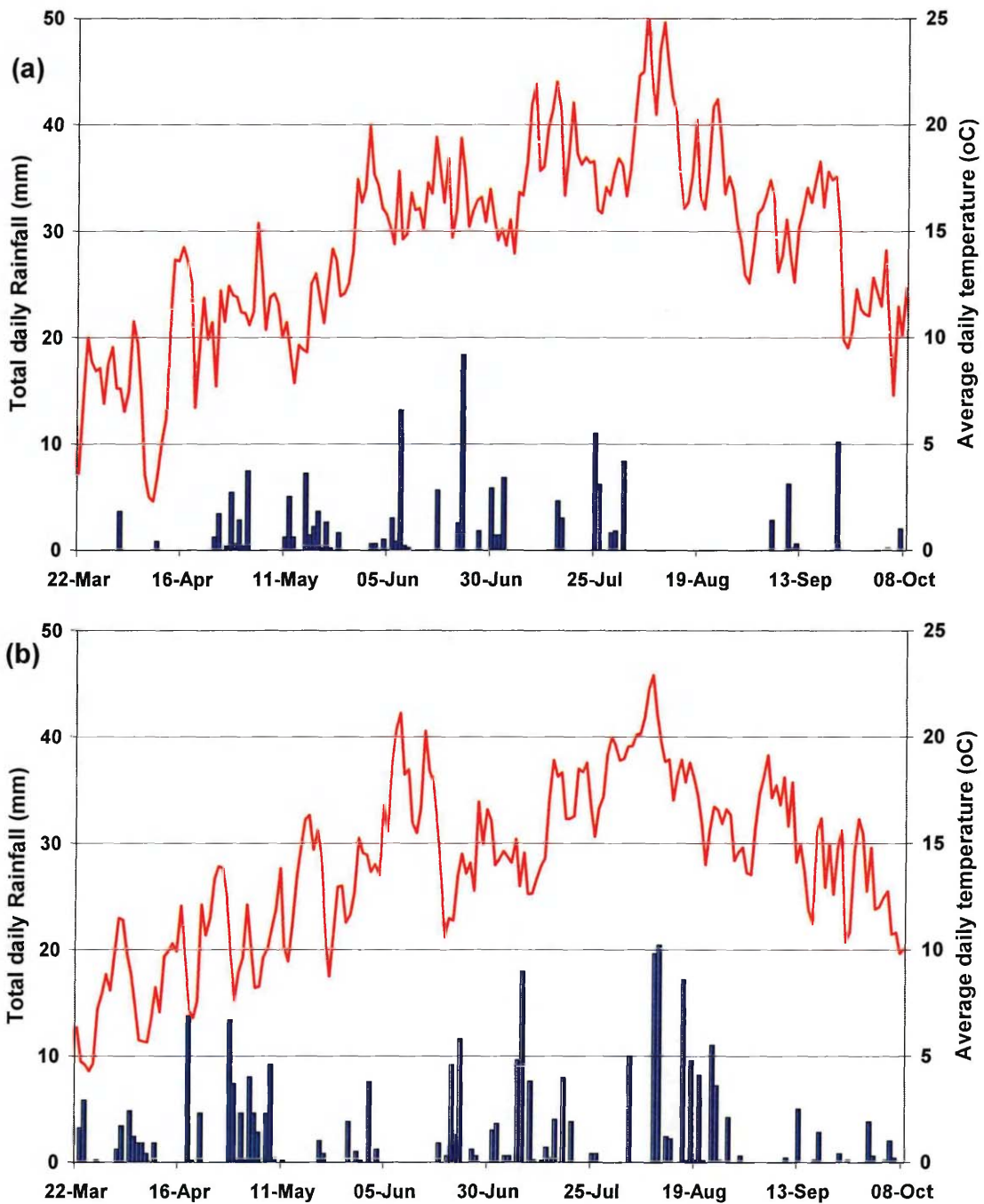


Figure 5-4 Daily rainfall and average daily temperatures (Data from Stone Hill weather station) for the time periods prior to the weekly soil moisture sampling at the Access tubes (a) 2003 (b) 2004

5.4 Soil moisture analysis

Several analyses were carried out separately to take account of the different average soil moisture conditions in combination with different weather conditions. The analyses were:

- Average soil moisture in each field for each of the sampling dates was plotted and the **average and standard errors** through the growing season were compared. The aim of this analysis was to examine the range of values across the field and see if they changed as the field dried out, were related to the measurement depth and how they related to meteorological conditions;
- The **Spearman's Rank Correlation Co-efficient** was calculated between soil moisture measurements in the field for each pair of dates (Vachaud *et al.*, 1985). This was repeated for each measurement depth. The resulting matrices can be found in Appendix VI. The aim of this analysis was to test for changes in the spatial patterns in the field and to make observations as to how the timing of these could be associated with particular meteorological conditions;
- The **relative differences** of the soil moisture values from the mean value of the field were plotted with the **standard deviation of these differences** over time shown (Vachaud *et al.*, 1985). The aim of this analysis was to test whether certain locations were consistently above or below the mean value for the field;
- The final analysis that was carried out was an **Analysis of Variance (ANOVA)**. This examined the variation in soil moisture with respect to soil series at 1:10,000 scale, soil texture at the measurement depth and depth within the soil profile.

In the literature the proportion of variance explained by terrain indices is a maximum of 60% and is generally lower than this (Western *et al.*, 2004) for large data sets, in excess of 100 points. A complete analysis of the soil moisture results with respect to

terrain indices was not carried out as this would have required analysis of each sample depth for each sampling event separately (Over 90 analyses for each of the three field/year combinations) but with less than 22 points in each analysis. A simple regression between all the samples and the terrain variables showed no significant correlation. It is thought that this is due to the terrain variables being measured at a different scale to the soil moisture – there were over 90 soil moisture results for a single value of a terrain variable.

5.5 Results

5.5.1 *Stone Hill 2003*

At 100 mm the **average soil moisture** in Stone Hill decreased, over the growing season, from 23% vol/vol to 9% vol/vol. There were four peaks in the soil moisture at 100 mm. These were on the 20th May, 11th June, 30th July and 12th September (Figure 5-5). They reflected the response of the soil to rainfall events in the week previous to the measurements (Figure 5-5). There was a 31 mm of rainfall in the 10 days previous to the 2nd July measurement, but the measured soil moisture appeared to reflect the broader trend of decreasing soil moisture. This was probably a result of increasing temperatures and therefore increasing evapotranspiration.

As the depth within the profile increases there is an increase in the variation of soil moisture across the field, shown in the increase in **standard error** (Figure 5-5). At 1 m depth the average soil moisture decreased from 33% vol/vol to 17% vol/vol. The trend at 1 m depth was much smoother than at 100 mm (Figure 5-5).

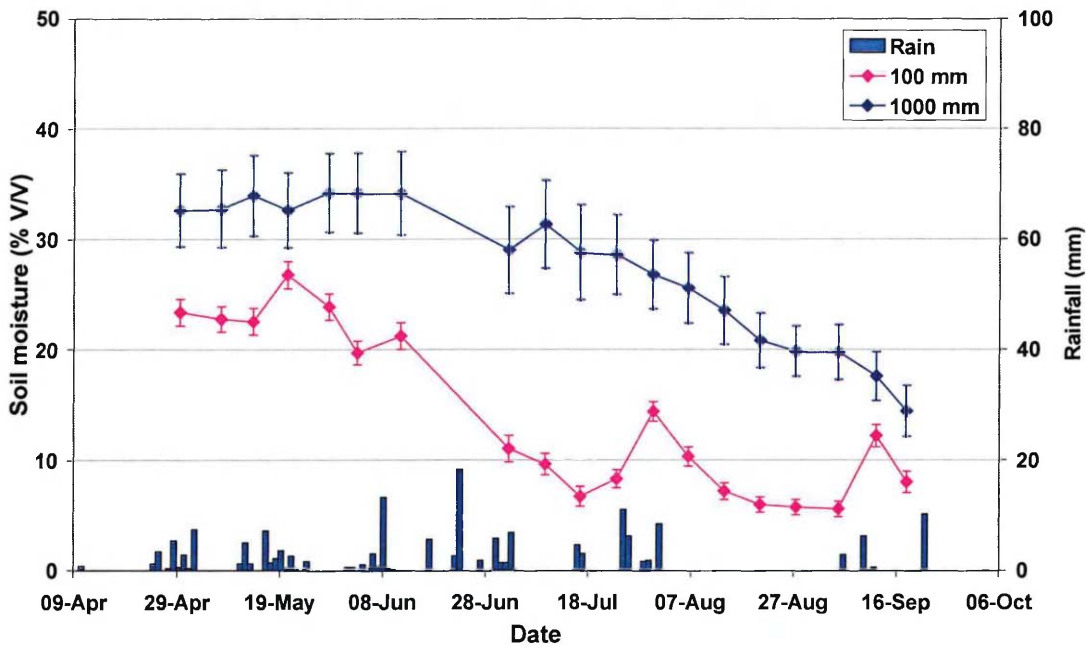


Figure 5-5 Average soil moisture (% vol/vol) in Stone Hill 2003 for each sampling date at 100 mm and 1 m. Error bars show the standard error on the mean.

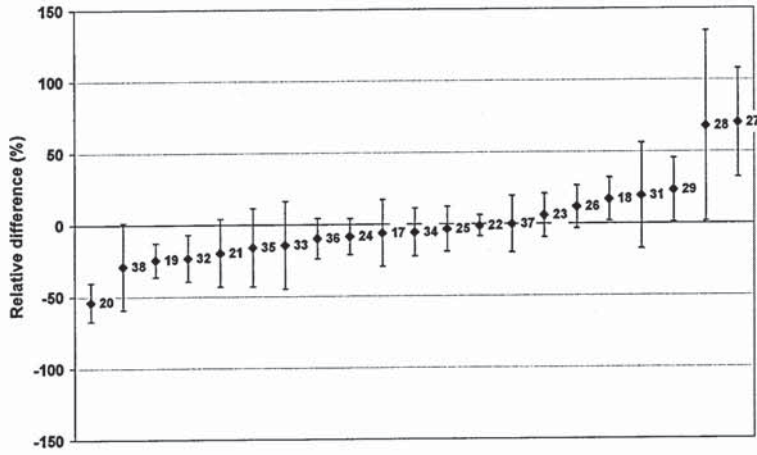
The resulting **Spearman's Rank Correlation Co-efficient** (Appendix VI) at 100 mm showed a fairly unstable pattern of soil moisture within the field, with only measurement depths close in time showing high correlations. At 200 mm there were an increased number of significant correlations between sampling dates. The significant correlations at both 100 mm and 200 mm depth fall into two groups (Figure 5-15). The spatial pattern of soil moisture is stable, showing significant correlations, from 29th April to the 11th June and then from the 2nd July to the 18th September (Appendix VI). This change in spatial pattern was linked to increased temperatures and later in the season, when temperatures decreased, very low rainfall (Figure 5-4). It could be linked to changing evapotranspiration characteristics. At increasing depths, from 300 mm to 1 m, the pattern of soil moisture within the field appeared to be stable, with significant Spearman's Rank Correlation Coefficients, throughout the growing season (Appendix VI). This could be due to the decreasing influence of evapotranspiration with increasing depths.

The **relative differences** from the mean were mainly between $\pm 50\%$ at 100 mm and 200 mm depth and then increase to $\pm 100\%$ with increasing depth. In general the standard deviations were less than $\pm 30\%$ (Figure 5-6). As the depth increases fewer

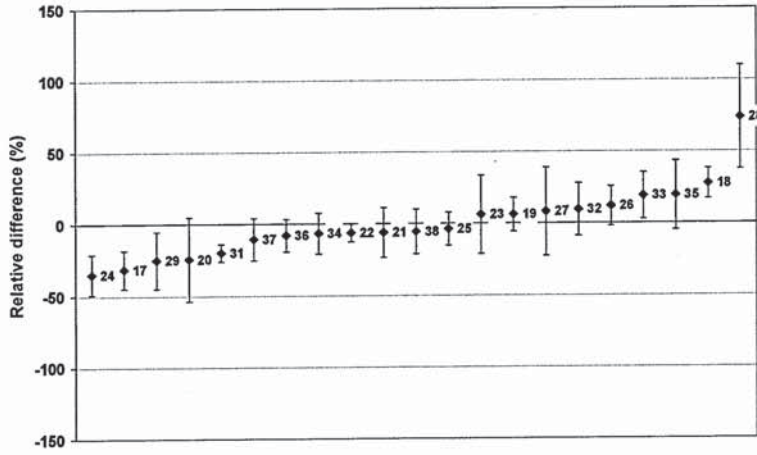
locations represent the mean value for the field, locations are either consistently higher or lower than the mean. The variability of soil moisture measurements across the field is also seen to increase with depth (Figure 5-5). These two findings correspond to an increase in the variation in soil texture with depth. At 100 mm the soil is either a sandy loam or loamy sand, where as at 1 m the soil texture ranges from sand to clay. In general the higher clay content soils are wetter and the soils with an increased sand content are drier. It is therefore expected that soil moisture measurements will show both greater variation and be less likely to represent the mean value as depth within the profile increases. At depths greater than 300 mm the points below the field mean soil moisture are more stable in time, have lower standard deviations, than locations with soil moistures greater than the field mean.

At given locations in the field points show different residuals from the mean value at different depths. For example at 100 mm and 200mm tube 22 represents the mean value for the field and has a very low standard deviation. At increasing depths, however the bias increases to 75% lower than the mean soil moisture (Figure 5-6).

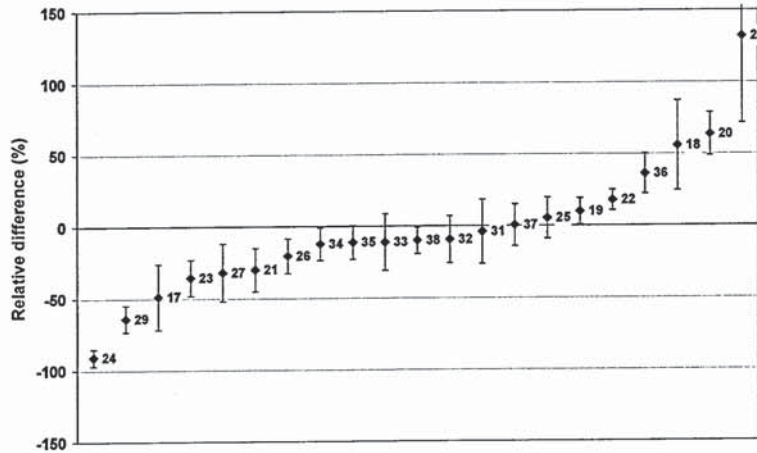
Stone Hill 2003 100 mm



Stone Hill 2003 200 mm



Stone Hill 2003 300 mm



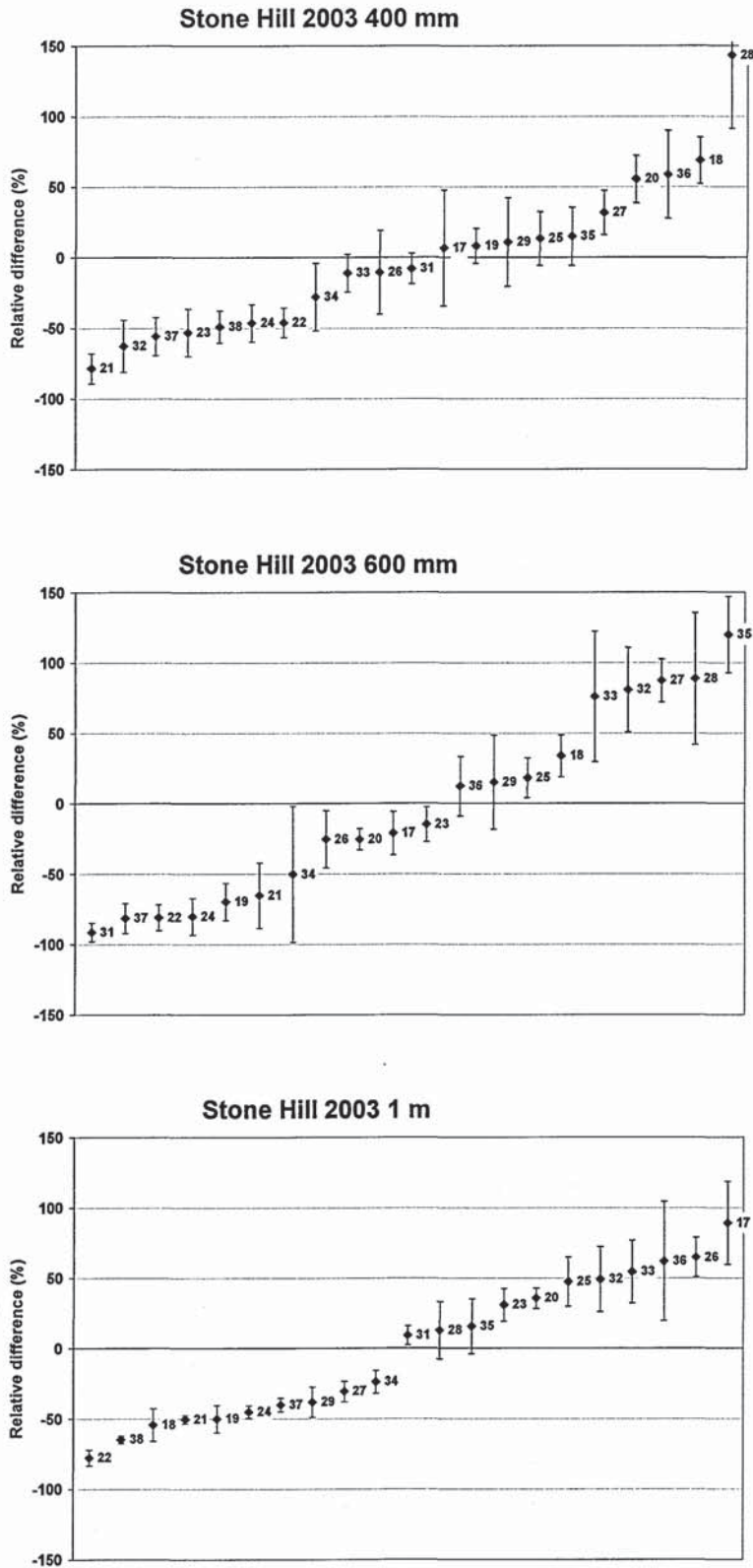


Figure 5-6 Relative differences from the field mean soil moisture for Stone Hill 2003. Error bars represent $\pm$ Standard deviation of the difference over the growing season

The results of **ANOVA** show that the soil moisture at 1 m was significantly higher than at any of the other sampling depths, this could be due to the influence of ground water at this depth (Figure 5-7). Soil series alone explains only 15% of the variation in soil moisture (Table 5-2). The soils though do fall into four distinct groups with different soil properties. These were consistent with results of the ANOVA of the surface soil moisture measurements in Stone Hill (Chapter 4). These groups (Figure 5-7) show differing soil properties (Table 3-1):

- Cuckney and Bearsted;
- Cottenham, Ebstree and Maplestead;
- Melford;
- Wix.

Results from the ANOVA show that 56% of the variation in soil moisture can be explained by a combination of depth and series.

Generally measurement points with a higher clay content showed significantly higher soil moisture than more sandy textures (Figure 5-7). This is due to the higher water holding capacity of clay soils. However the texture at the measurement depth explains almost 30% less variation in soil moisture than a combination of depth and series at 1:10,000 scale (Table 5-2).

Table 5-2 Variance explained by soil properties and depth

Factor	Variance explained
Soil Texture class	27%
Soil Series	15%
Depth and Series	56%
Depth and Texture	*

*Incomplete design in that not all textures are represented at all depths

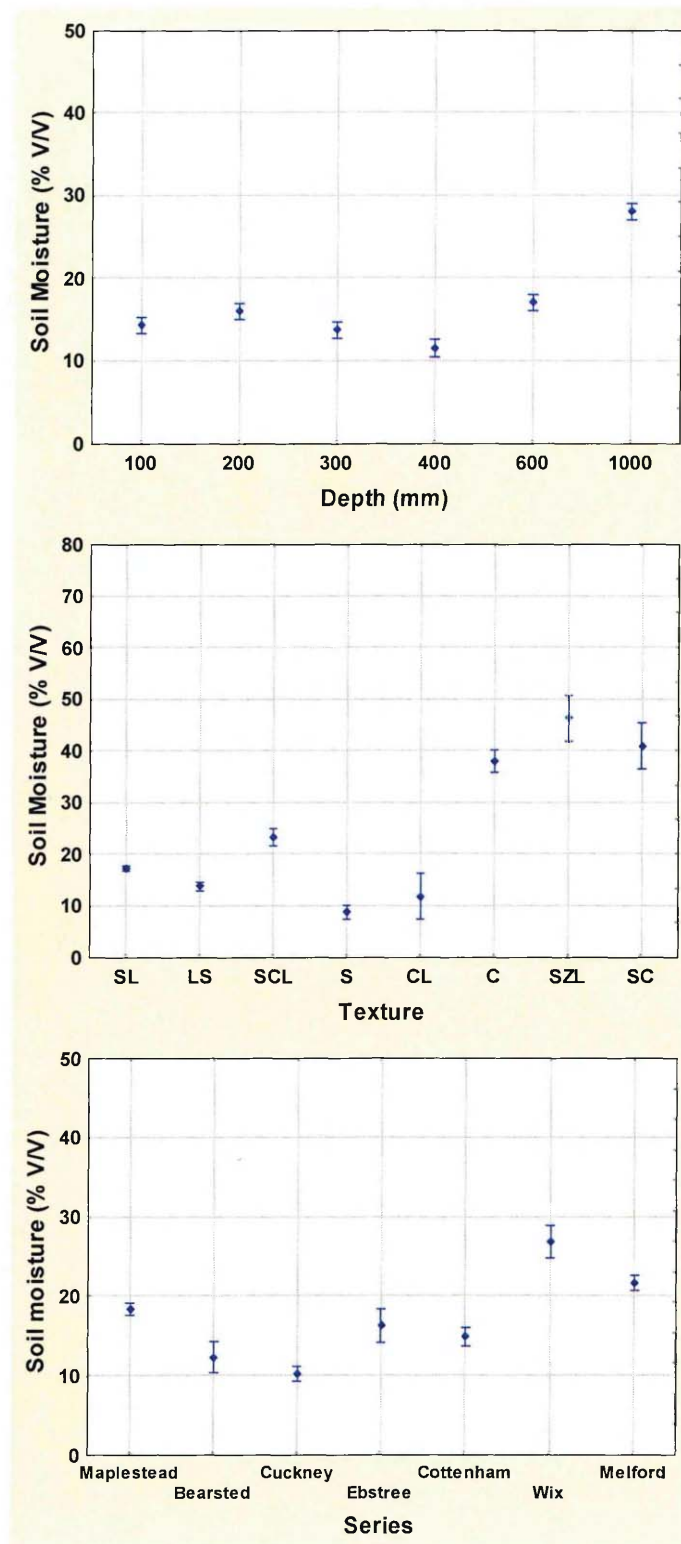


Figure 5-7 Results of the ANOVA for soil moisture average soil moisture in Stone Hill 2003 with respect to (a) Depth (b) Soil texture at the measurement point (LS-Loamy Sand SCL-Sandy Clay Loam S- Sand CL-Clay Loam SZL-Sandy Silt Loam SC-Sandy Clay) (c) 1:10,000 scale soil series. Error bars show the 95% confidence interval

5.5.2 Stone Hill 2004

There was a decrease in the **average soil moisture**, in Stone Hill, at the beginning of the season at both 100 mm and 1 m compared to 2003 (Figure 5-8). This is thought to be due to the lower rainfall in the previous Summer, Autumn and Winter of 2003 than in 2002. A key feature in the average soil moisture patterns at 100 mm in 2004 is the decrease in soil moisture to the 18th June and the subsequent increase until the 6th August (Figure 5-8). This was linked to two weeks with no rainfall prior to sampling on the 18th June and a large amount of rainfall at the end of June and through July (Figure 5-4), where the total rainfall was above the 30 year average (Figure 4-1). The three peaks, on the 10th May, 25th June and 8th July are, as in 2003, associated with increased rainfall in the week previous to sampling. At 1 m depth the average soil moisture increases from 29% vol/vol to 42% vol/vol. The soil moisture at 1 m shows much less of a smooth trend than in 2003. The largest increase is between the 6th and 10th May (Figure 5-8). This is associated with 56 mm rain in the two weeks prior to the 10th May. The range of values, shown by the **standard error on the mean**, increased with increasing depths as in 2003.

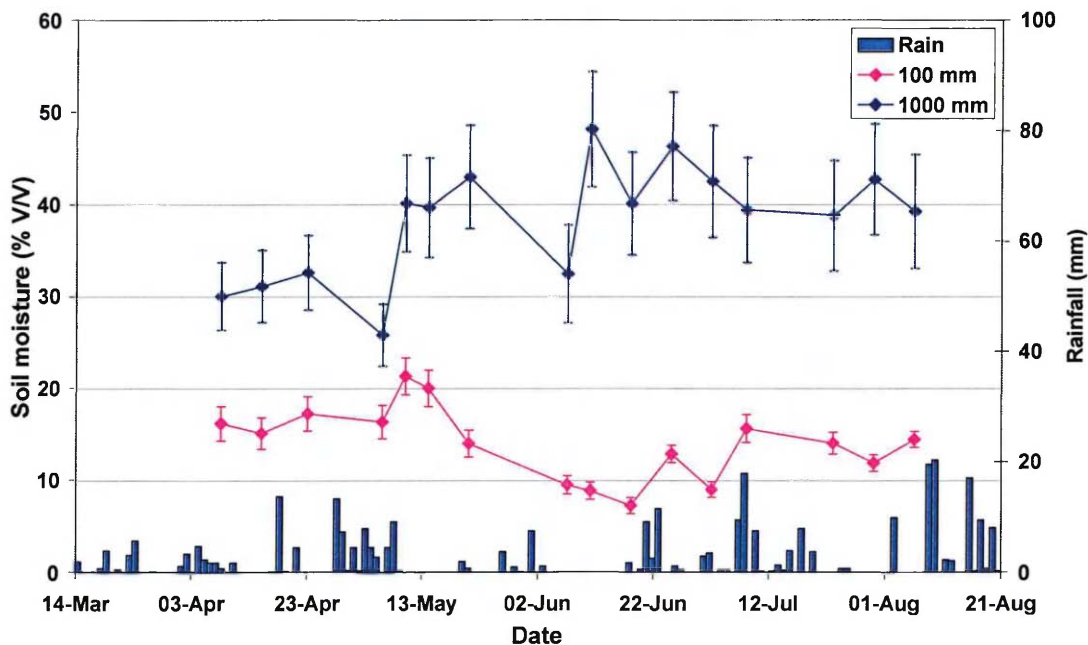
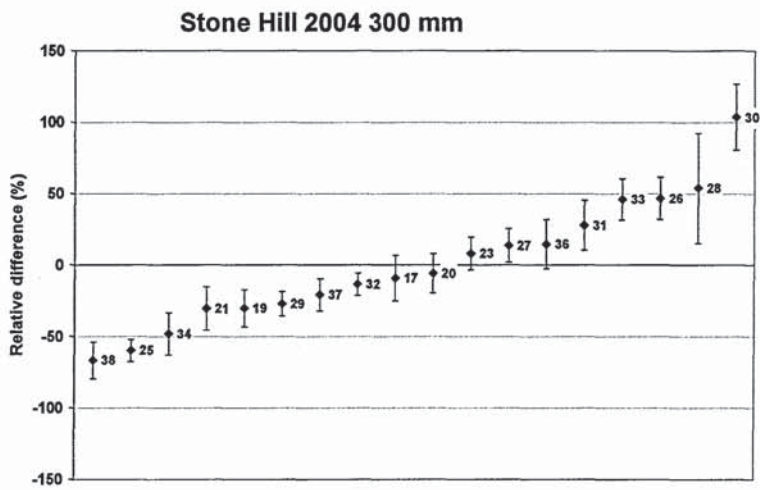
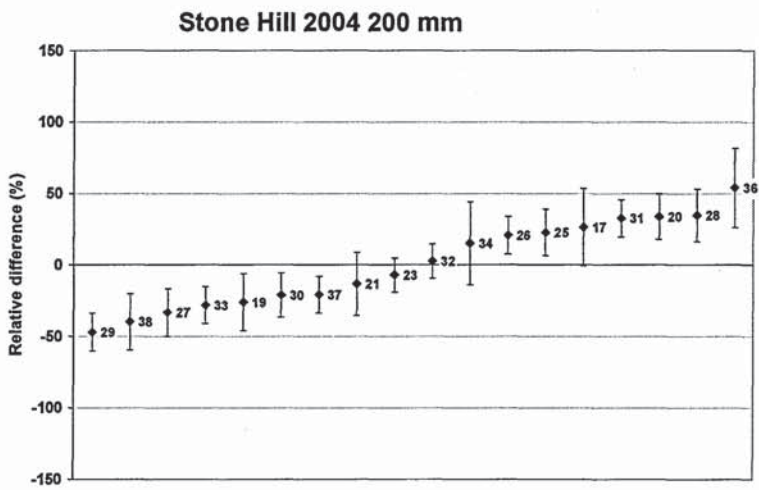
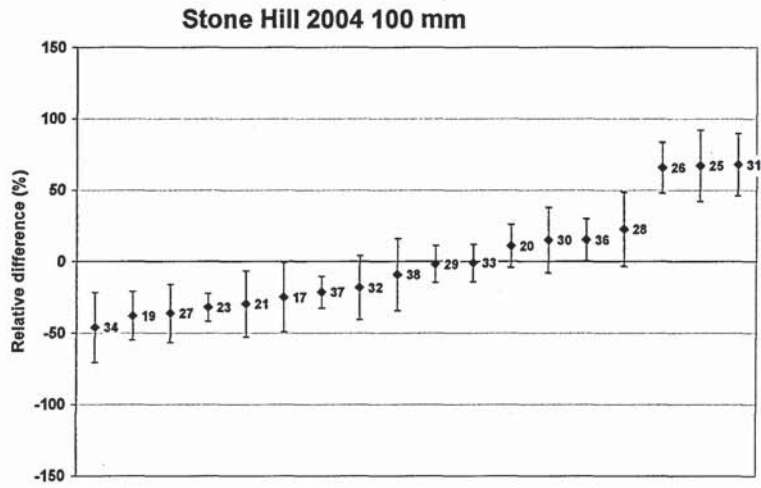


Figure 5-8 Average soil moisture (% vol/vol) in Stone Hill 2004 for each sampling date at 100 mm and 1 m. Error bars show the standard error on the mean

The results from the **Spearman's Rank Correlation Co-efficient** (Appendix VI) showed, as in 2003, that the correlations between dates are quite scattered in the top 200mm, although most are significant. The lowest and in many cases non significant correlations are associated with 30th July (Figure 5-15). This comes after a 10 day dry period combined with an increase in temperature (Figure 5-4). The correlations between sampling dates, as in 2003 increased with increasing depth. This again could be linked to the decrease in the effects of evapotranspiration on soil moisture at increasing depths.

The results from 2004 show that the majority of locations have **mean relative differences** up to $\pm 50\%$ to a depth of 300 mm and as in 2003 the number outside this range increases with increasing depth (Figure 5-9). This corresponds to the increase in the variation in soil texture with depth. At 100 mm the soil is either a sandy loam or loamy sand, where as at 1 m the soil texture ranges from sand to clay. In general the standard deviations in the top 200 mm are greater than in 2003. However, these as in 2003, decrease throughout the soil profile (Figure 5-9). The standard deviations of the points are generally lower at the points which are below the average field soil moisture. In general there are fewer locations in 2004, at any depth, that represent the average soil moisture in the field compared to 2003.



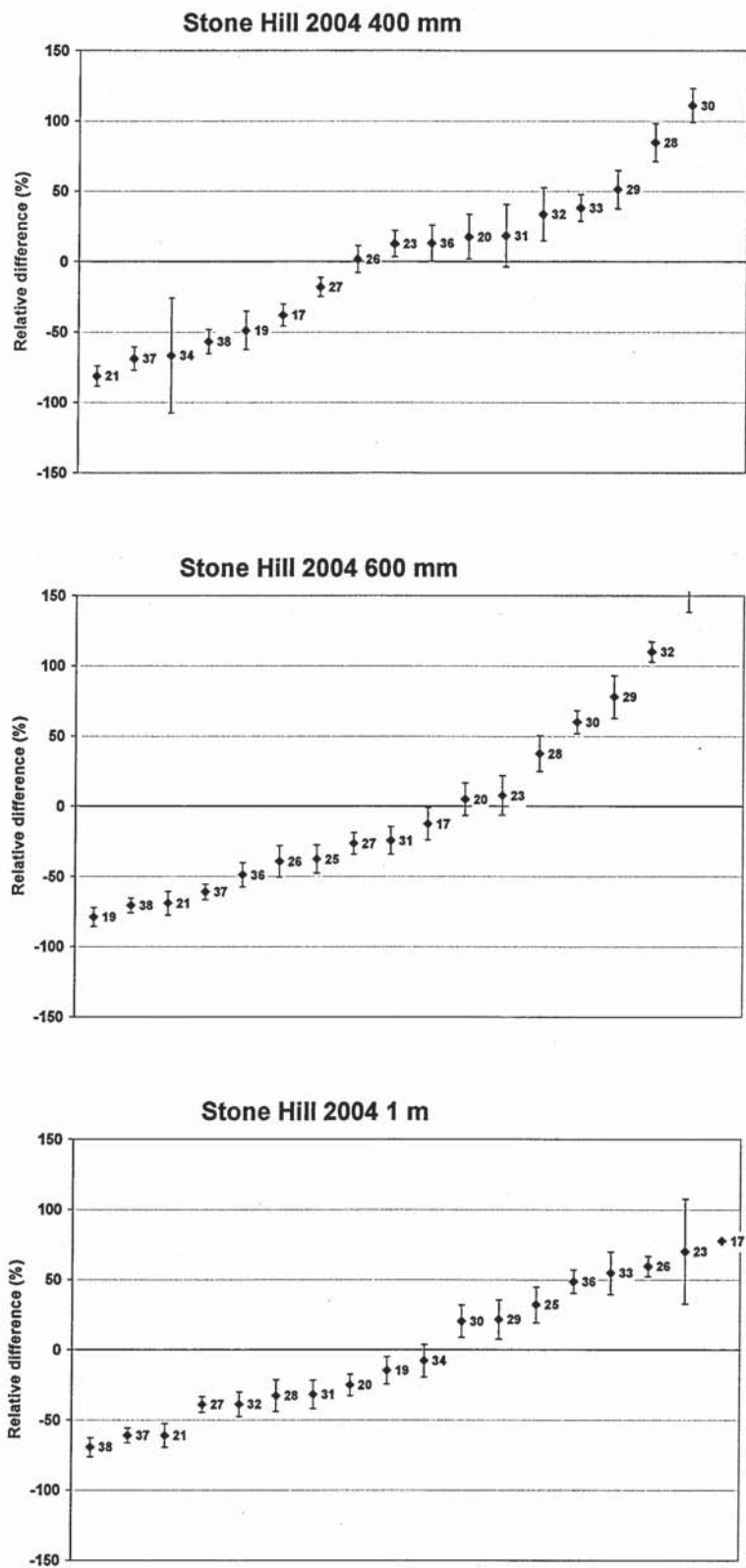


Figure 5-9 Relative differences from the field mean soil moisture for Stone Hill 2004. Error bars represent +/- Standard deviation of the difference over the growing season

The results of **ANOVA** show that the soil moisture at 600 mm and 1 m were significantly higher than at any of the other sampling depths, this could be due to the influence of ground water at this depth. The increase in soil moisture at 600 m compared to in 2003 is thought to be due to increasing precipitation and decreased temperatures leading to soil moisture recharge over the growing season (Figure 5-4). The soils though do fall into three distinct groups with different soil properties (Table 3-1). These groups (Figure 5-10) are:

- Cuckney and Bearsted;
- Cottenham;
- Ebstree, Maplestead, Melford and Wix.

The results from the ANOVA show that an increased proportion of the variation in soil moisture, 66%, is explained by a combination of series at 1:10,000 scale and depth within the profile than in 2003 (Table5-3). Texture again explains approximately 30% less of the variation in soil moisture than the combination of depth and series.

Soils with a clays (C) and sandy, silt loam (SZL) texture have very high soil moisture (Figure 5-10). This could be due to their high water holding capacity, but also their association with horizons deep in the soil profile which became saturated over the measurement period.

Table 5-3 Variance explained by soil properties and depth

Factor	Variance explained
Soil Texture class	37%
Soil Series	15%
Depth and Series	66%
Depth and Texture	*

*Incomplete design in that not all textures are represented at all depths

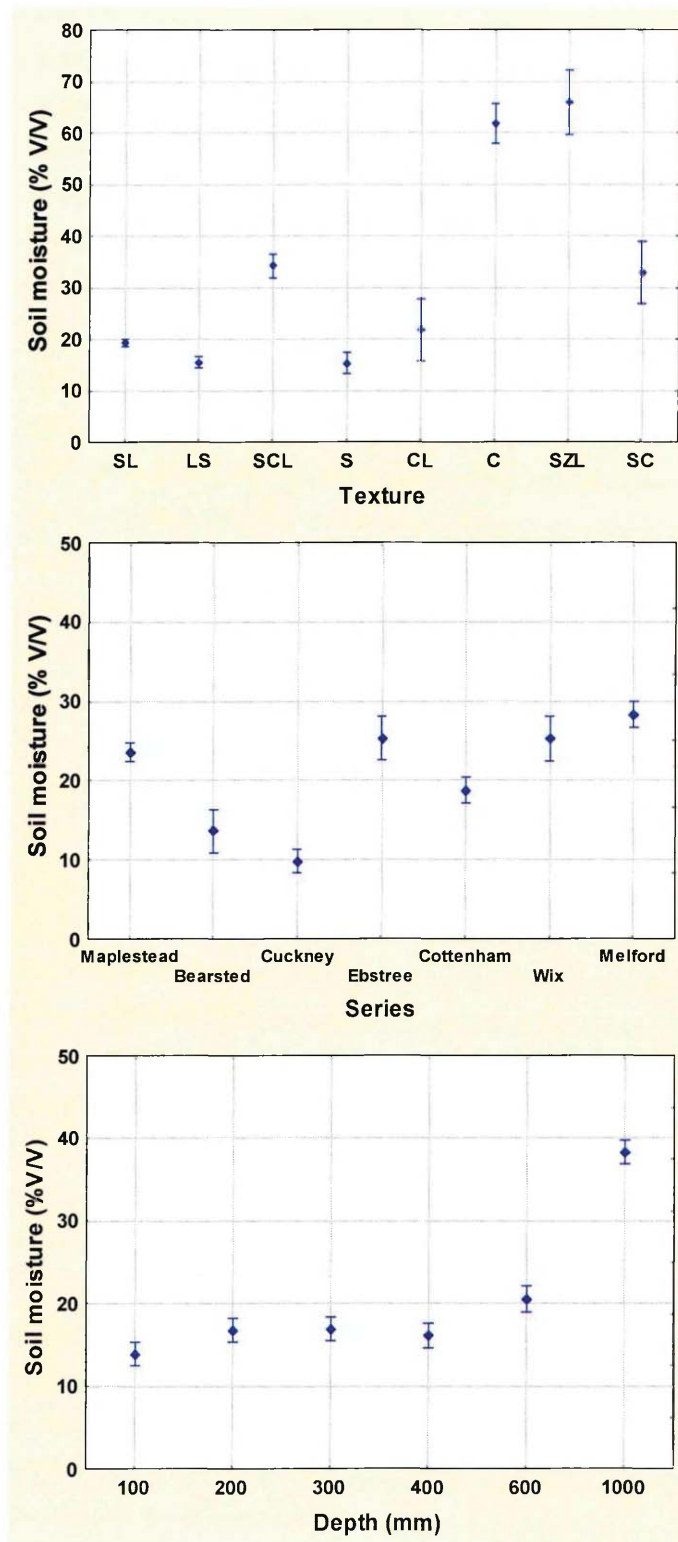


Figure 5-10 Results of the ANOVA for soil moisture average soil moisture in Stone Hill 2004 with respect to (a) Depth (b) Soil texture at the measurement point (LS-Loamy Sand SCL-Sandy Clay Loam S- Sand CL-Clay Loam SZL-Sandy Silt Loam SC-Sandy Clay) (c) 1:10,000 scale soil series. Error bars show the 95% confidence interval

5.5.3 Stone Hill discussion

The ANOVA from the surface surveys pick out similar soil groups to those from the profiles. In the surface surveys Maplestead is not distinguishable from Melford. When the depth measurements are taken into account the soil types become distinguishable. This can be explained by the clay at depth within the Melford series, which would be expected to have a higher water content than the sandy base of the Maplestead profile, but both series would be expected to be freely draining with respect to the surface measurements.

The clay loam soil texture showed lower soil moisture with respect to the other more sandy soil textures, in both 2003 and 2004. This could be caused by other drainage characteristics associated with the soil profile at tube 20.

5.5.4 Church Meadow 2003

The **average soil moisture** in Church meadow, as in Stone Hill in 2003, decreases over the growing season. At 100 mm the average soil moisture decreases from 18% to 7%. There were three peaks in the soil moisture at 100 mm. These were on the 20th May, 11th June and 30th July (Figure 5-11). They reflected the response of the soil to rainfall events in the week previous to the measurements (Figure 5-4). At 1 m depth the average soil moisture decreases from 32% vol/vol to 14% vol/vol. As in Stone Hill in 2003 the response to individual rainfall events can be seen in the 100 mm measurements, but this becomes less evident with increasing depth. Furthermore the increase in **standard error on the mean** with increasing depth could be linked to increased variation in soil texture with increasing depth as in Stone Hill.

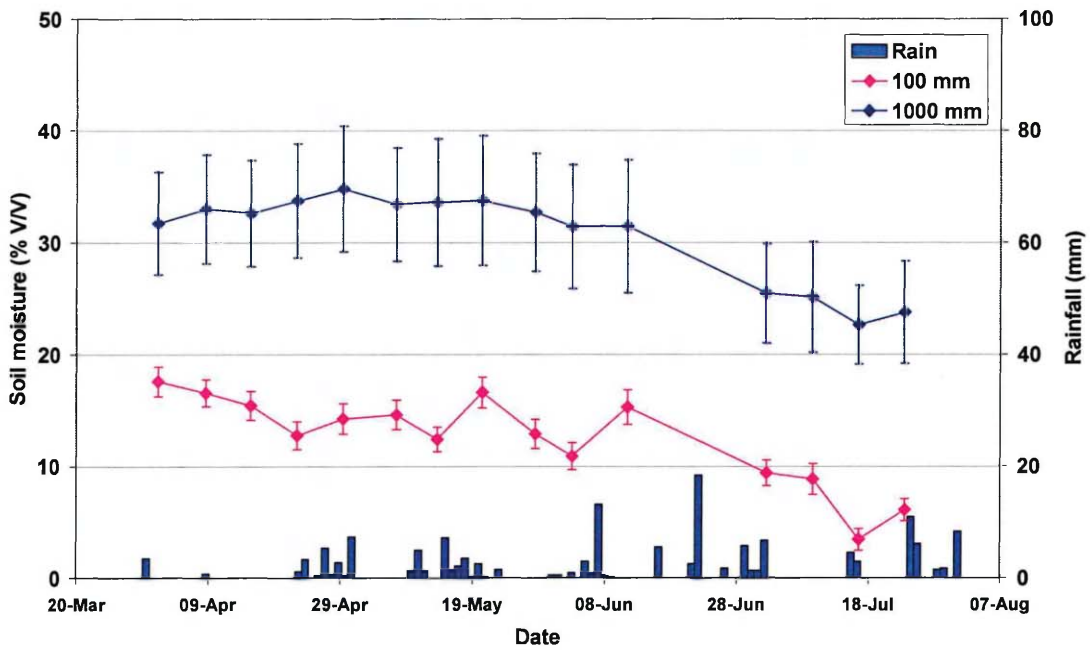


Figure 5-11 Average soil moisture (% vol/vol) in Church Meadow-2003 for each sampling date at 100 mm and 1 m. Error bars show the standard error on the mean

The results from the **Spearman's Rank Correlation Co-efficient** (Appendix VI) analysis show that the spatial patterns of soil moisture become more stable with increasing depth through the profile. In the top 400 mm there is a decrease in the correlations between the dates after the 11th June and those earlier (Figure 5-15). This change in spatial pattern was linked to increased temperatures and later in the season, when temperatures decreased, very low rainfall (Figure 5-4). This phenomenon is not as pronounced in Church Meadow as in Stone Hill this could be due to the smaller overall decrease in soil moisture (Figure 5-11) and the shorter time period over which sampling took place.

The results that the majority of locations have **mean relative differences** up to $\pm 50\%$ to a depth of 400 mm and as in 2003 the number outside this range increases with increasing depth. The standard deviations in the top 100 mm are greater than in Stone Hill in 2003, but as in Stone Hill they decrease throughout the soil profile (Figure 5-12).

The results of the **ANOVA** (Figure 5-13) show 67% of the variation in soil moisture can be explained by a combination of series at 1:10,000 scale and depth (Table 5-4).

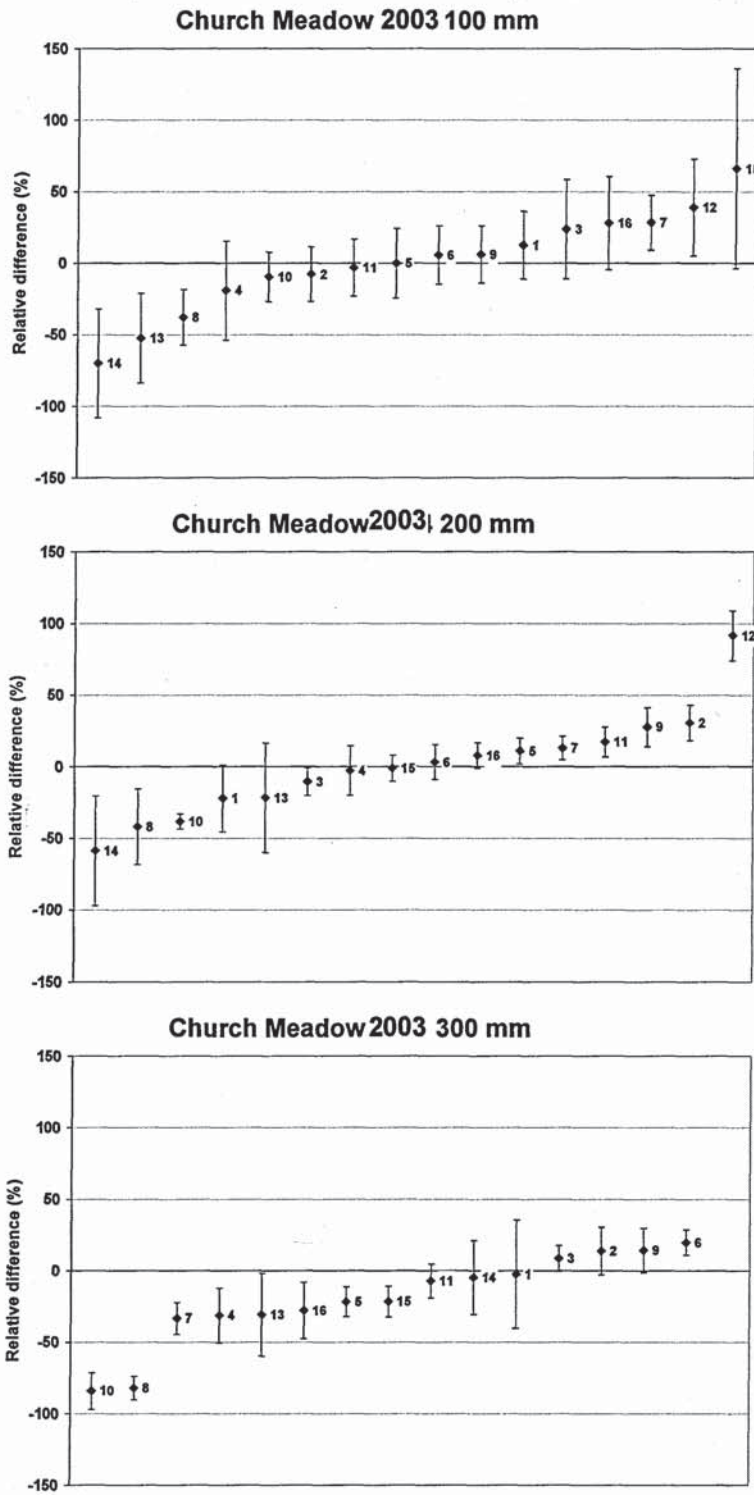
More of the variation can be explained by soil texture at the measurement depth than in Stone Hill. The soil series alone explains 31% of the variation in soil moisture compared to about 15% in Stone Hill. The soils fall into four groups reflecting their soil properties (Table 3-1):

- Bearsted and Cuckney;
- Maplestead;
- Hanslope;
- Ashley.

Table 5-4 Variance explained by soil properties and depth

Factor	Variance explained
Soil Series	31%
Depth and Series	67%
Depth and Texture	*

Incomplete design in that not all textures are represented at all depths



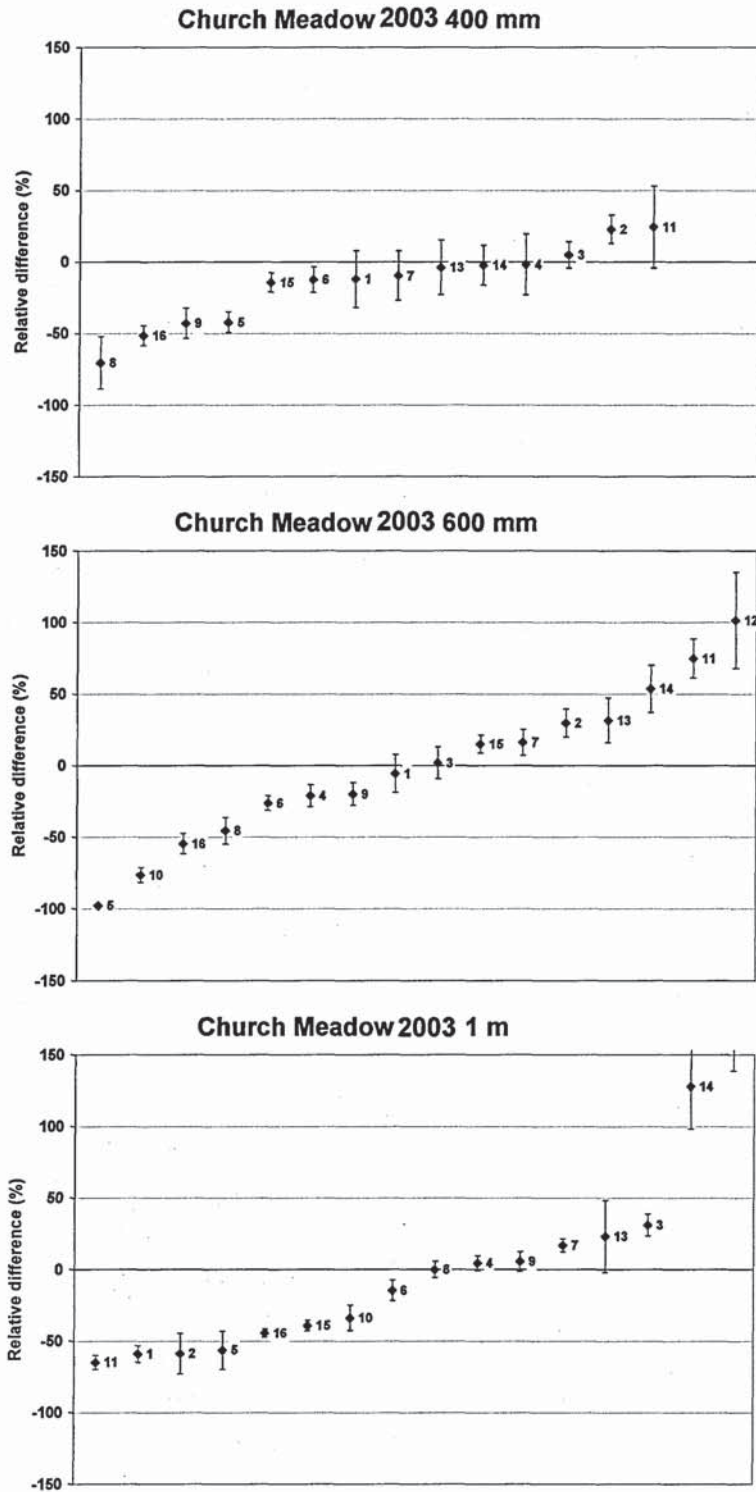


Figure 5-12 Relative differences from the field mean soil moisture for Church meadow in 2003. Error bars represent $\pm$ Standard deviation of the difference over the growing season

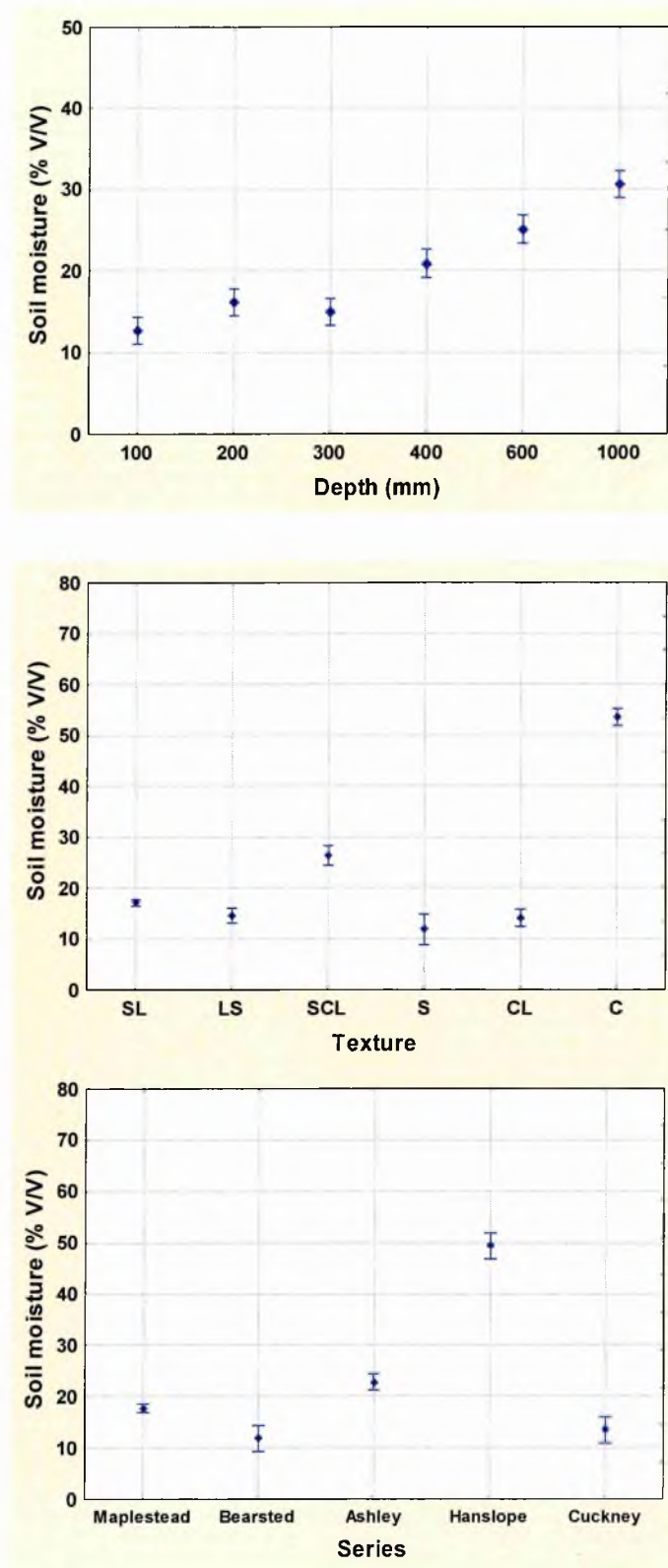


Figure 5-13 Results of the ANOVA for soil moisture average soil moisture in Church Meadow 2003 with respect to (a) Depth (b) Soil texture at the measurement point (LS-Loamy Sand SCL-Sandy Clay Loam S- Sand CL-Clay Loam SZL-Sandy Silt Loam SC-Sandy Clay) (c) 1:10,000 scale soil series. Error bars show the 95% confidence interval

5.6 Discussion

The results in this chapter suggest that soil moisture shows spatial patterns in the landscape, which are primarily linked to soil properties. More specifically:

- The flat areas and areas at the base of the fields (Figure 5-14, location 3), such as tube 17, tend to have increased soil moisture at depth;



Figure 5-14 Photograph of Stone Hill showing (1) Flat area at the top of the field (2) Most steeply sloping area (3) Base of the field adjacent to the water course

- At a point scale soil texture is a driver of soil moisture, as horizons with high clay and silt content generally have higher soil moisture. This is expected as clay and silt increase the water holding capacity of the soil;
- As the variations in texture increase soil moisture becomes increasingly varied and fewer locations represent the mean soil moisture in the field;
- The average soil moisture varies with soil series. Soil series are determined at the 1:10,000 scale which suggests that, at a field scale, drainage characteristics within the soil profile are more important in determining the soil moisture at a given depth than the specific texture at the measurement depth. The combination of texture and depth could not be analysed as all the textures did not occur at every depth. These results highlight the complex non linear interactions between soil moisture, soil and terrain as

noted in the literature (Mohanty and Skaggs, 2001, Jacobs *et al.*, 2004, Lin *et al.*, 2006)

In Stone Hill in 2003 there is a change in the pattern of soil moisture in the surface layers between the beginning and end of the season. This is consistent with the observations by Martínez-Fernández and Ceballos, (2003) who suggest that there is a change in the patterns of soil moisture in a field from wet to dry periods. This could reflect a change in driving processes in wetter and drier conditions as suggested by Wilson *et al.*, (2005). In general the patterns of soil moisture are more stable with increasing depth as in the study by Martínez-Fernández and Ceballos, (2003). This suggests that landscape position, and characteristics, are likely to predict soil moisture at depth more consistently than at the surface. The analysis of the spatio-temporal variation of soil moisture with respect to topographic characteristics did not show any conclusive results. However overall:

- The results from the soil moisture access tubes are consistent with the surface soil moisture surveys;
- The amount of variation of soil moisture explained by soil series in Church Meadow is greater than in Stone Hill;
- The soils fall into very similar groups as in the ANOVA carried out on the surface surveys. These reflected the drainage characteristics of the soils, although when the soil moisture at depth was taken into account some soils, which showed the same surface soil moisture, showed significantly different soil moisture. This reflected changes in texture in the soil profile;
- The surface measurements reflect the recent rainfall events.

This study has shown that the spatial patterns of soil moisture in the field become more stable with depth. However the locations of points in the surface layer that represent the average soil moisture in the field are not necessarily the same as those which represent the average soil moisture at a greater depth. The movement of soil moisture with respect to the mean with increasing depth highlights the point made by Fernandez-Gálvez *et al.*, (2006) that snap shots of soil moisture through a profile can lead to a bias in the estimate of soil water in the profile. It also shows that care must

be taken when interpreting surface measurements from remotely sensed data. These record the soil moisture at the surface and may not necessarily reflect the soil moisture at deeper levels in the soil. Further analysis which could be carried out on this data set would be to compare the temporally stable points at 100 mm to the average values over the 1 m depth.

The results shown here indicate a similar periodicity in the soil moisture at different time scales as suggested by Lauzon *et al.*, (2004) and Parent *et al.*, (2006). The longer term, variations are associated with drying out of the soil over the season in the very dry year and the instability of the shorter term variations in the top 100 mm suggests a link to rainfall events.

5.7 Major results

The key results from this chapter are that:

- Soil moisture variability across the field increases with depth for any given date;
- Soil moisture variability at a specific location decreases with depth;
- The drainage characteristics within the soil profile appear to be more important in determining the soil moisture than the texture at the measurement depth.

5.8 Implications for the STAMINA model

The results outlined in this chapter show significant relationships with soil characteristics and taxonomic soil groups. In this landscape the processes governing soil water distribution appear to be more strongly linked to soil characteristics than directly to terrain. The ability of the STAMINA model to represent soil water dynamics based on soil properties should therefore be investigated.

Stone Hill 2003 100 mm

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03
29-Apr-03	1.00	0.95	0.83	0.90	0.84	0.51	0.52	0.07	0.14	0.13	0.03	0.14	0.04	0.11	-0.03	0.01	0.07	0.13	0.24
7-May-03	0.95	1.00	0.86	0.86	0.89	0.53	0.48	0.12	0.16	0.14	0.04	0.23	0.04	0.13	-0.04	0.02	0.07	0.10	0.23
13-May-03	0.83	0.88	1.00	0.85	0.92	0.68	0.59	0.22	0.20	0.11	0.05	0.14	0.06	0.11	0.07	-0.02	-0.03	0.29	0.21
20-May-03	0.90	0.86	0.85	1.00	0.84	0.51	0.57	0.37	0.23	0.24	0.15	0.28	0.13	0.18	0.03	0.08	0.15	0.33	0.26
28-May-03	0.84	0.89	0.82	0.84	1.00	0.70	0.68	0.28	0.24	0.16	0.07	0.20	0.09	0.18	-0.01	0.04	0.09	0.22	0.13
3-Jun-03	0.51	0.53	0.68	0.51	0.70	1.00	0.82	0.40	0.52	0.26	0.27	0.16	0.26	0.33	0.24	0.19	0.34	0.35	0.35
11-Jun-03	0.52	0.48	0.59	0.57	0.68	0.82	1.00	0.56	0.42	0.28	0.29	0.23	0.32	0.38	0.27	0.26	0.37	0.51	0.35
2-Jul-03	0.07	0.12	0.22	0.27	0.28	0.40	0.56	1.00	0.54	0.46	0.64	0.72	0.60	0.54	0.43	0.48	0.45	0.67	0.43
9-Jul-03	0.14	0.16	0.20	0.23	0.24	0.52	0.42	0.54	1.00	0.83	0.88	0.62	0.80	0.87	0.75	0.75	0.72	0.26	0.69
16-Jul-03	0.13	0.14	0.11	0.24	0.16	0.26	0.28	0.46	0.83	1.00	0.90	0.61	0.88	0.95	0.89	0.91	0.83	0.12	0.73
23-Jul-03	0.03	0.04	0.05	0.15	0.07	0.27	0.29	0.64	0.88	0.90	1.00	0.76	0.93	0.93	0.88	0.91	0.79	0.33	0.78
30-Jul-03	0.14	0.23	0.14	0.28	0.20	0.16	0.23	0.72	0.62	0.61	0.76	1.00	0.72	0.71	0.64	0.71	0.62	0.47	0.67
6-Aug-03	0.04	0.04	0.06	0.13	0.09	0.26	0.32	0.60	0.80	0.88	0.93	0.72	1.00	0.94	0.91	0.95	0.76	0.32	0.81
13-Aug-03	0.11	0.13	0.11	0.18	0.18	0.33	0.38	0.54	0.87	0.95	0.83	0.71	0.94	1.00	0.92	0.95	0.81	0.27	0.82
20-Aug-03	-0.03	-0.04	-0.07	0.03	-0.01	0.24	0.27	0.43	0.75	0.89	0.88	0.64	0.91	0.92	1.00	0.98	0.90	0.25	0.83
27-Aug-03	0.01	0.02	-0.02	0.08	0.04	0.19	0.26	0.48	0.75	0.91	0.91	0.71	0.95	0.95	0.98	1.00	0.86	0.27	0.76
4-Sep-03	0.07	0.07	-0.03	0.15	0.09	0.34	0.37	0.45	0.72	0.83	0.79	0.62	0.76	0.81	0.90	0.86	1.00	0.22	0.76
12-Sep-03	0.13	0.10	0.29	0.33	0.22	0.35	0.51	0.67	0.28	0.12	0.33	0.47	0.32	0.27	0.25	0.27	0.22	1.00	0.38
18-Sep-03	0.24	0.23	0.21	0.26	0.13	0.35	0.35	0.43	0.69	0.73	0.78	0.67	0.81	0.82	0.82	0.83	0.76	0.38	1.00

Stone Hill 2004 100mm

Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.94	0.82	0.67	0.82	0.84	0.84	0.82	0.76	0.74	0.76	0.67	0.70	0.60	0.33	0.48
15-Apr-04	0.94	1.00	0.82	0.74	0.85	0.86	0.90	0.85	0.76	0.71	0.77	0.70	0.74	0.74	0.45	0.61
23-Apr-04	0.82	0.82	1.00	0.67	0.80	0.94	0.87	0.92	0.81	0.84	0.85	0.71	0.81	0.68	0.34	0.52
6-May-04	0.67	0.74	0.67	1.00	0.88	0.75	0.70	0.63	0.53	0.43	0.50	0.55	0.55	0.48	0.11	0.41
10-May-04	0.82	0.85	0.80	0.88	1.00	0.82	0.85	0.78	0.65	0.57	0.60	0.59	0.57	0.53	0.12	0.43
14-May-04	0.84	0.86	0.94	0.75	0.82	1.00	0.89	0.95	0.88	0.86	0.87	0.81	0.87	0.76	0.41	0.64
21-May-04	0.84	0.90	0.87	0.70	0.85	0.89	1.00	0.90	0.83	0.79	0.79	0.79	0.77	0.75	0.43	0.62
7-Jun-04	0.82	0.85	0.92	0.63	0.78	0.95	0.90	1.00	0.90	0.89	0.90	0.83	0.89	0.79	0.49	0.52
11-Jun-04	0.76	0.76	0.81	0.53	0.65	0.88	0.83	0.90	1.00	0.97	0.86	0.86	0.86	0.75	0.53	0.61
18-Jun-04	0.74	0.71	0.84	0.43	0.57	0.86	0.79	0.89	0.97	1.00	0.86	0.83	0.86	0.73	0.55	0.59
25-Jun-04	0.76	0.77	0.85	0.50	0.60	0.87	0.79	0.90	0.86	0.86	1.00	0.81	0.93	0.79	0.64	0.66
2-Jul-04	0.67	0.70	0.71	0.55	0.59	0.81	0.79	0.83	0.86	0.83	0.81	1.00	0.92	0.85	0.67	0.76
8-Jul-04	0.70	0.74	0.81	0.55	0.57	0.87	0.77	0.89	0.86	0.86	0.93	0.92	1.00	0.86	0.70	0.75
23-Jul-04	0.60	0.74	0.68	0.48	0.53	0.76	0.75	0.79	0.75	0.73	0.79	0.85	0.86	1.00	0.83	0.89
30-Jul-04	0.33	0.45	0.34	0.11	0.12	0.41	0.43	0.49	0.53	0.55	0.64	0.67	0.70	0.83	1.00	0.89
6-Aug-04	0.48	0.61	0.52	0.41	0.43	0.64	0.62	0.62	0.61	0.59	0.66	0.76	0.75	0.89	0.89	1.00

Church Meadow 2003 100 mm

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.94	0.73	0.74	0.63	0.61	0.57	0.60	0.60	0.31	0.50	0.24	0.30	0.32	0.31
8-Apr-03	0.94	1.00	0.75	0.72	0.58	0.58	0.56	0.64	0.69	0.29	0.46	0.32	0.34	0.35	0.41
15-Apr-03	0.73	0.75	1.00	0.93	0.75	0.92	0.86	0.81	0.84	0.60	0.72	0.60	0.69	0.61	0.78
22-Apr-03	0.74	0.72	0.93	1.00	0.85	0.84	0.89	0.86	0.92	0.73	0.85	0.64	0.74	0.60	0.73
29-Apr-03	0.63	0.58	0.75	0.85	1.00	0.70	0.82	0.73	0.74	0.66	0.78	0.70	0.62	0.78	0.67
7-May-03	0.61	0.58	0.92	0.84	0.70	1.00	0.89	0.69	0.76	0.69	0.66	0.56	0.70	0.63	0.75
13-May-03	0.57	0.56	0.86	0.89	0.82	0.89	1.00	0.83	0.83	0.72	0.76	0.64	0.80	0.67	0.77
20-May-03	0.60	0.64	0.81	0.86	0.73	0.69	0.83	1.00	0.85	0.49	0.79	0.61	0.60	0.47	0.63
28-May-03	0.60	0.69	0.84	0.92	0.74	0.76	0.83	0.85	1.00	0.77	0.77	0.65	0.73	0.58	0.76
3-Jun-03	0.31	0.29	0.60	0.73	0.66	0.69	0.72	0.49	0.77	1.00	0.77	0.67	0.87	0.59	0.70
11-Jun-03	0.50	0.46	0.72	0.85	0.78	0.66	0.76	0.79	0.77	0.77	1.00	0.74	0.79	0.65	0.76
2-Jul-03	0.24	0.32	0.60	0.64	0.70	0.56	0.64	0.61	0.65	0.67	0.74	1.00	0.78	0.77	0.86
9-Jul-03	0.30	0.34	0.69	0.74	0.62	0.70	0.80	0.60	0.73	0.87	0.79	0.78	1.00	0.67	0.86
16-Jul-03	0.32	0.35	0.61	0.60	0.78	0.63	0.67	0.47	0.58	0.59	0.65	0.77	0.67	1.00	0.80
23-Jul-03	0.31	0.41	0.78	0.73	0.67	0.75	0.77	0.63	0.76	0.70	0.76	0.86	0.86	0.80	1.00

Figure 5-15 Spearmans Rank Correlation Matrices for 100 mm depth for Church Meadow and Stone Hill (See Appendix VI for full details)

6 Regional application of the STAMINA model

6.1 Approach

This chapter outlines the approach taken to the application of the STAMINA model at a regional level. It addresses:

- The **method** by which terrain indices were used, their selection and how this links to the field results outlined in chapters 4 and 5;
- The **selection of representative catchments** in which to apply both versions of the model;
- The **regression approach** for combining the results of the two versions of the model in attempt to improve the prediction of the regionalised model.

It shows the results from the test areas within the study area and **addresses the question**: “Is the proposed index based method applicable for the regional application of the STAMINA model?”

6.2 Index based method

The STAMINA model concept is outlined in Chapter 1. The physically based model formulation is then discussed along with the topographic parameters which are required to distribute the meteorological variables to each cell in the landscape. The version of the STAMINA model used in this analysis was version 1.8. This research investigates changing the form of this part of the model to an index based approach (Figure 6-1). This involved using SSWI, SWRSS and Temperature, calculated in TAPES-G and SRAD respectively, to distribute rainfall, radiation and temperature in the landscape. The following discussion examines the method by which these terrain variables are used in the index based version of the STAMINA model.

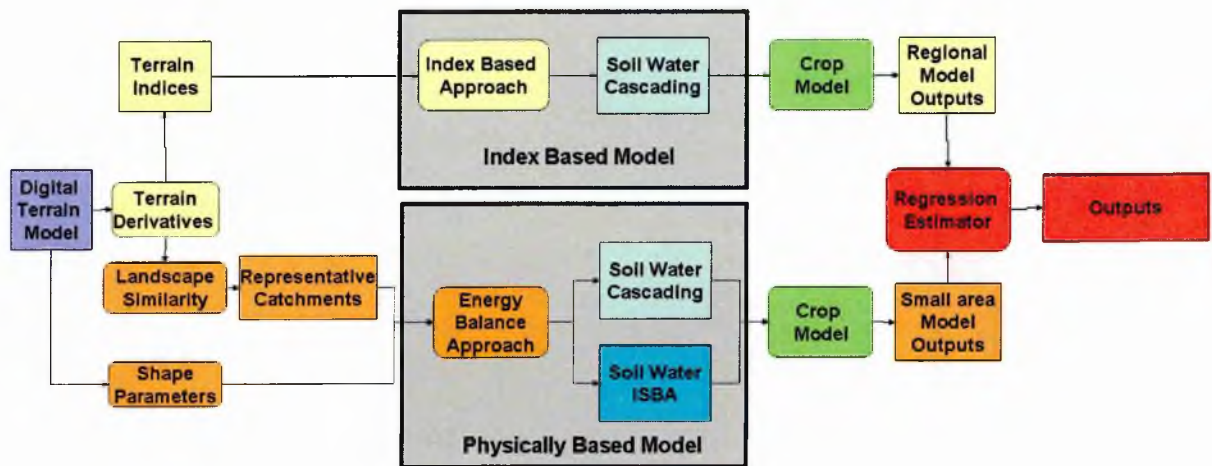


Figure 6-1 The two approaches to the application of the STAMINA model, showing how terrain variables are input into a micrometeorological module (Index based or Energy balance) which links to a soil hydrology module and then into the crop growth module. The concept was then to improve the index based approach based on a regression estimator

the rainfall, global radiation and temperature measured at the base station were scaled based on the SSWI, SWRSS and Average Temperature calculated using TAPES-G. and SRAD respectively (Figure 6-2). The scaling process divided each of the outputs from TAPES-G by the value at the point where the meteorological variables were measured. This ensured the value of the index at the reference point was one. These adapted meteorological parameters were input directly into the crop growth model. The physically based approach required hourly meteorological data inputs. Regional meteorological stations only record daily data. In order for the model to make use of daily data, the cascading approach to distributing water within the soil profile was required.

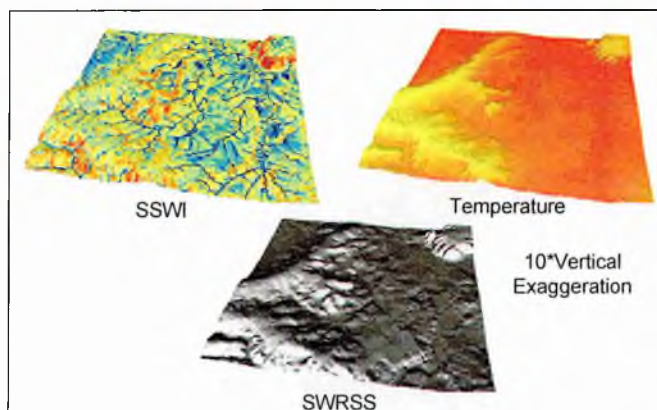


Figure 6-2 The three indices used in the index method for applying the STAMINA model at a regional level. Shown for the 10 km² study area in Bedfordshire

This approach was chosen as it:

- Fitted within the modular framework of the STAMINA model;
- Soil moisture surveys, chapters 4 and 5, showed that terrain variables combined with soil data were a useful and simple way of predicting soil moisture in the landscape. This was particularly the case in the most steeply sloping areas of the landscape. Terrain in the study area explained up to 41% and terrain plus soils up to 79% variation in surface soil moisture. These, more steeply sloping areas, were the areas of interest for the STAMINA project;
- The SSWI was selected over the DYNWI because it gave similar results but was much simpler to calculate. It only required a DTM and not soils data;
- The SWRSS was selected due to its physically based approach, and that it could be calculated in the same suite of software packages as SSWI.

6.3 Selecting representative catchments

Representative areas of the landscape needed to be defined if the outputs of the two methods were to be accurately compared, and any conclusions drawn valid were to be across the region. If meaningful regression relationships between the two versions of the model, in small areas, could be developed then these could be used to improve the estimates of the regional level model (Taylor *et al.*, 1997). In order to achieve this, a method of selecting these small areas within the landscape was required, which ensured that they were representative of the wider landscape. The method for selecting these representative areas was to use the software package CAS (Figure 6-3) (Behrens *et al.*, Unpublished).

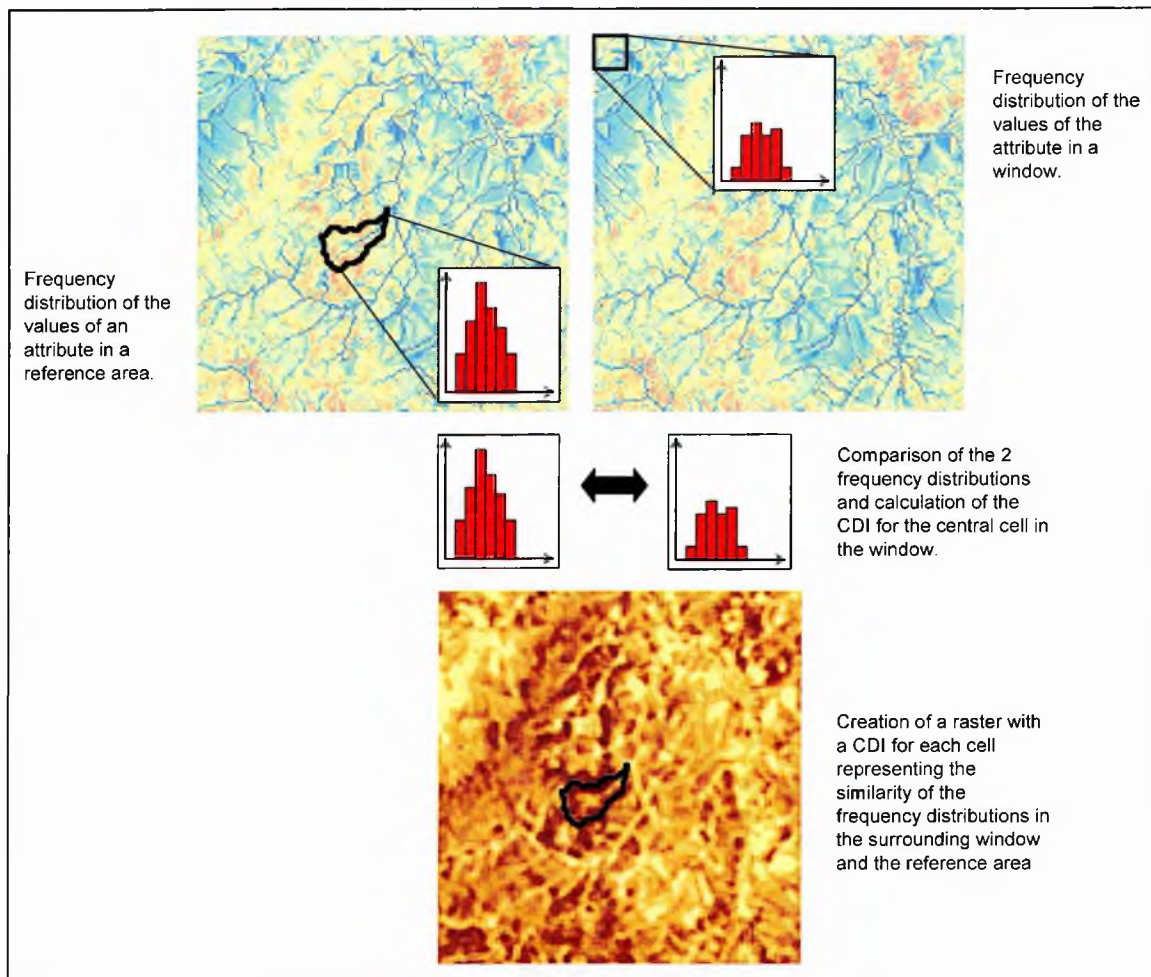


Figure 6-3 The principles behind CAS (Behrens et al., unpublished)

6.3.1 Method

In order to analyse the sensitivity of the model to terrain complexity, catchments which represented the hilly regions of the landscape were required. CAS was run to select catchments, which together represent the SSWI and SWRSS at a regional extent. The SSWI and SWRSS were divided into 100 classes based on equal interval breaks. This was done because CAS does not accept continuous input variables. The landscape was divided into small sub-catchments using ArcHydro Tools (Maidment, 2002) within ArcGIS. The upslope area was decreased until areas, small enough to run the model (a few hundred 50 m cells), were delineated. The first representative sub-catchment was selected on the basis that it contained two of the experimental fields (Stone Hill and Church Meadow). CAS was then run for each 50 m cell using this as a reference area. The search radius was 200 m square and the tolerance was 100%. The similarity index, CDI, was then mapped for each 50 m DTM grid cell. Zonal statistics in ArcGIS were used to calculate the average CDI in each of the small sub-

catchments. Further sub-catchments for analysis were selected based on the following criteria, that they:

- Showed low similarity values with respect to the SSWI and SWRSS;
- Were in different major catchments;
- Contained a significant proportion of land with a slope greater than 3°;
- Represented the different soil series at 1:25,000 within the region (Figure 6-3).

After completing this process two catchments were identified that could possibly be used on the ridge in the west of the area. From these catchments a third field was chosen, its catchment becoming the second representative catchment (Figure 6-4). The third representative catchment was then selected in the north east corner of the study area (Figure 6-4).

Further analysis was then carried out using CAS for both the SSWI and SWRSS. The areas within each of the catchments greater than 3° were input into CAS as reference areas. CAS was run for each 50 m cell above 3° slope, using a search radius of 200 m square and tolerance of 100%. A raster was created by overlaying the three CDI grids and selecting the maximum similarity for each cell. This was done using the raster calculator tool in ArcGIS.

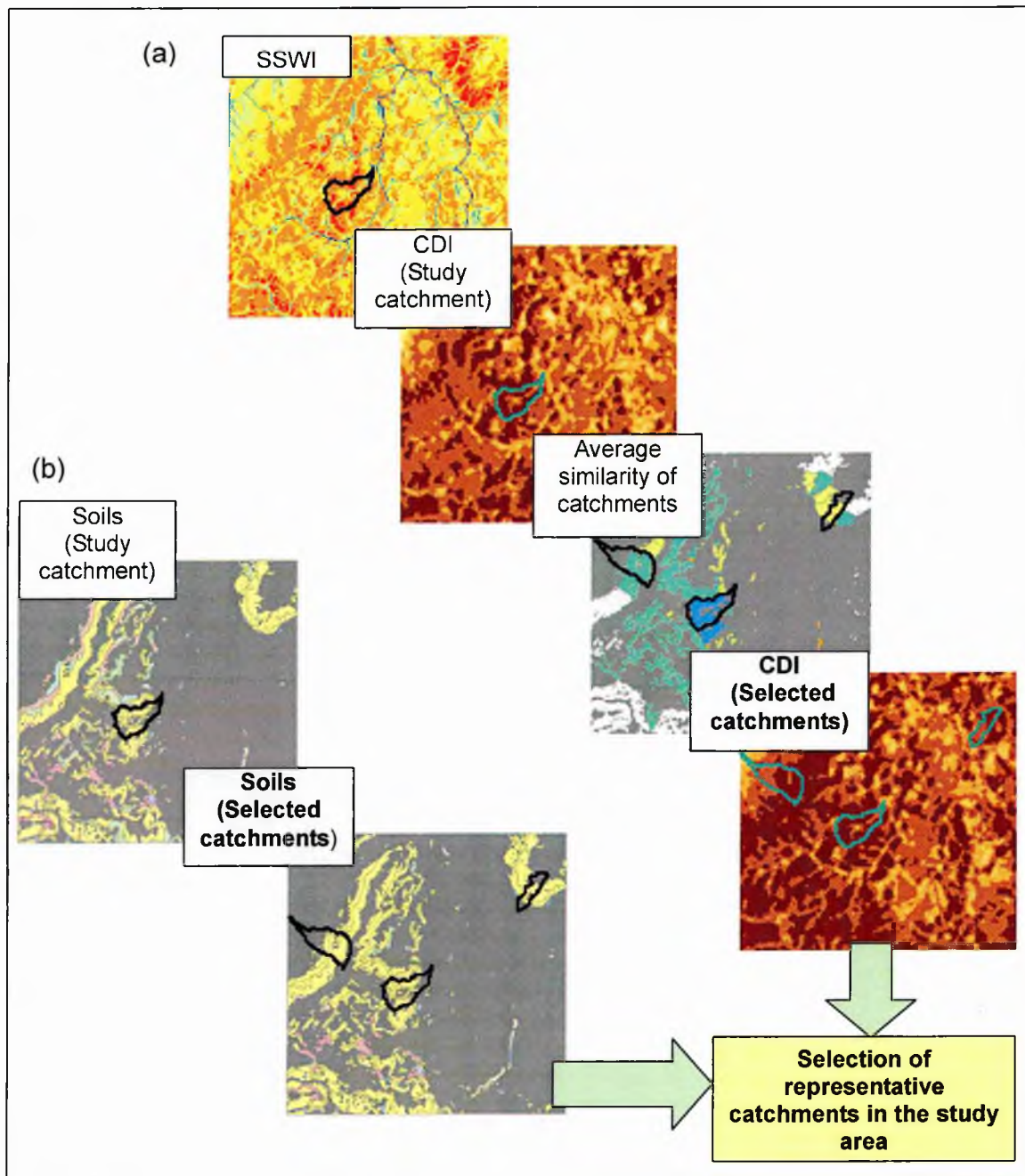


Figure 6-4 Methodology for selecting representative catchments (a) Showing the use of the SSWI and the improvement in the representation of the Study Area between using one catchment and 3, shown by plotting the CDI index from CAS (Behrens, 2003 personal communication) (b) Selecting an increased number of catchments increases the number of soils that are represented. The masked areas show areas less than 3° slope

6.3.2 Selection of representative catchments in the study area

The objective of running CAS was to show that adding catchments into the representative area increased the areas with high similarity to the reference point. The results from running CAS on the areas greater than 3° slope show that adding the catchment in the west of the study area increases the representation of the steeply sloping upper part of the ridge both in the SWRSS (Figure 6-5) and SSWI (Figure 6-6). The CDI output from CAS shows that adding the catchment from the north east of the area does not appear to add any further highly representative areas to either the SSWI or SWRSS in the study area. However the histograms for the region and the reference map show that it does pick up some of the areas in the classes lower than 15 (Figure 6-7). This catchment is therefore important. It also represents a different part of the region on the opposite side of the River Ivel to the two other catchments.

The results from CAS show that adding catchments leads to a better representation of the study area (Figures 6-5 and 6-6). The results can be plotted spatially and the areas which are not well represented identified. The subset histograms from the three catchments combined show a similar shape and range to the total area (Figure 6-7). Figure 6-8 shows the SSWI, SWRSS and 1:25,000 soil series boundaries for each of the areas with greater than 3° slope in the representative catchments selected by CAS.

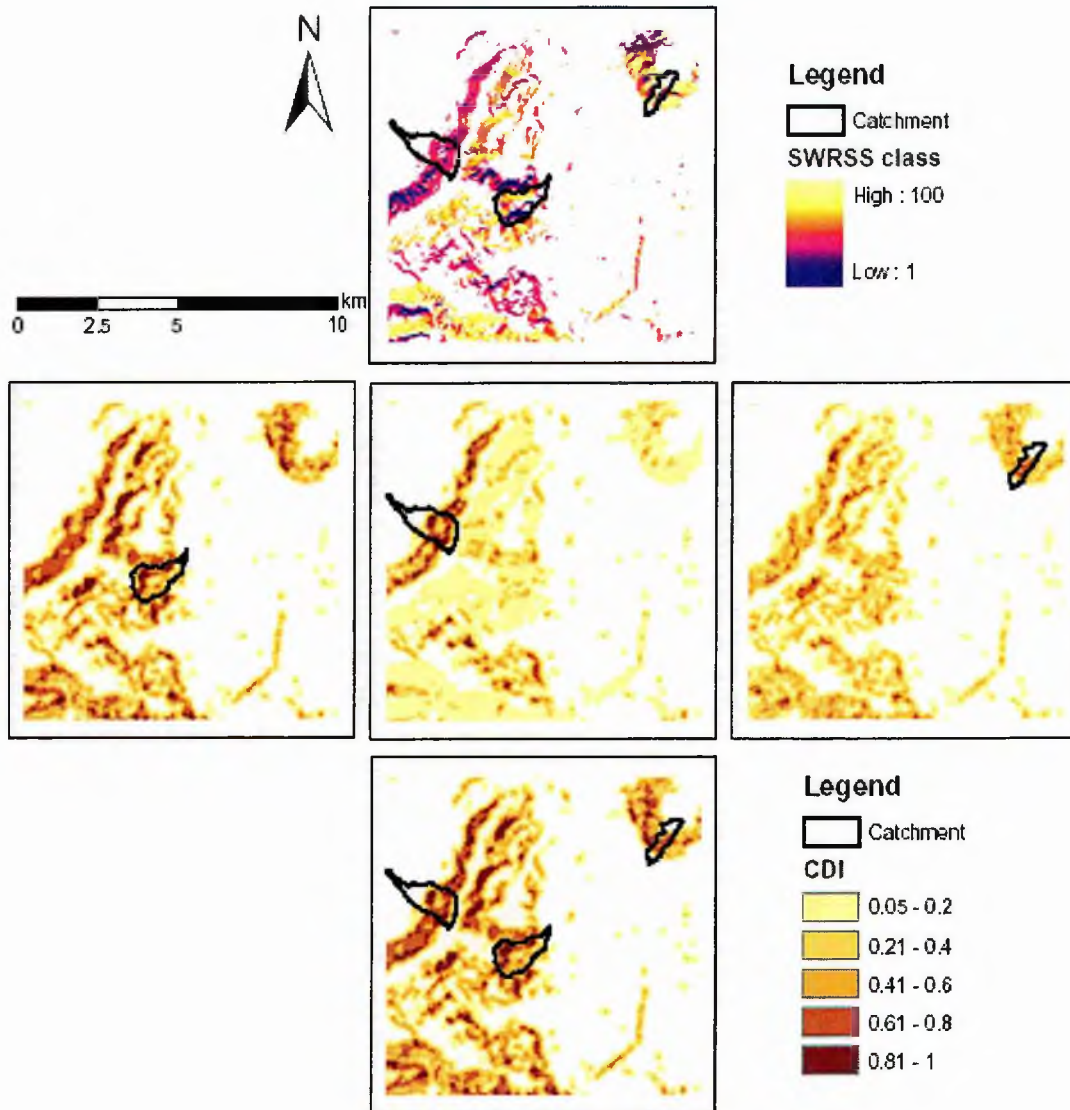


Figure 6-5 CAS run for SWRSS (Top) SWRSS divided into 100 classes (Middle) The CDI results from running CAS for each of the representative catchments (Bottom) and The maximum CDI for all of the catchments (Bottom) The masked areas show areas less than 3°slope

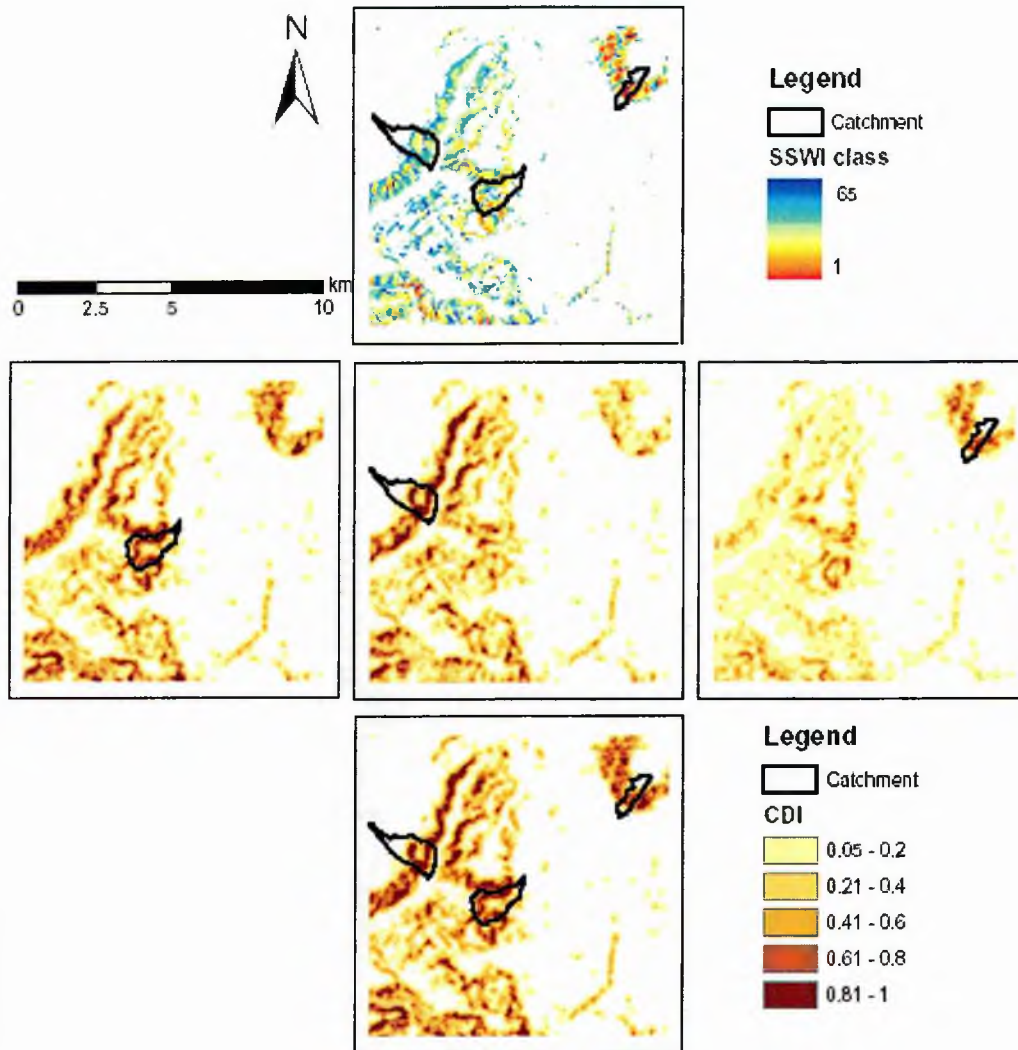


Figure 6-6 CAS run for SSWI (Top) SSWI divided into 100 classes (Middle) The CDI results from running CAS for each of the representative catchments (Bottom) and The maximum CDI for all of the catchments (Bottom) The masked areas show areas greater than 3° slope

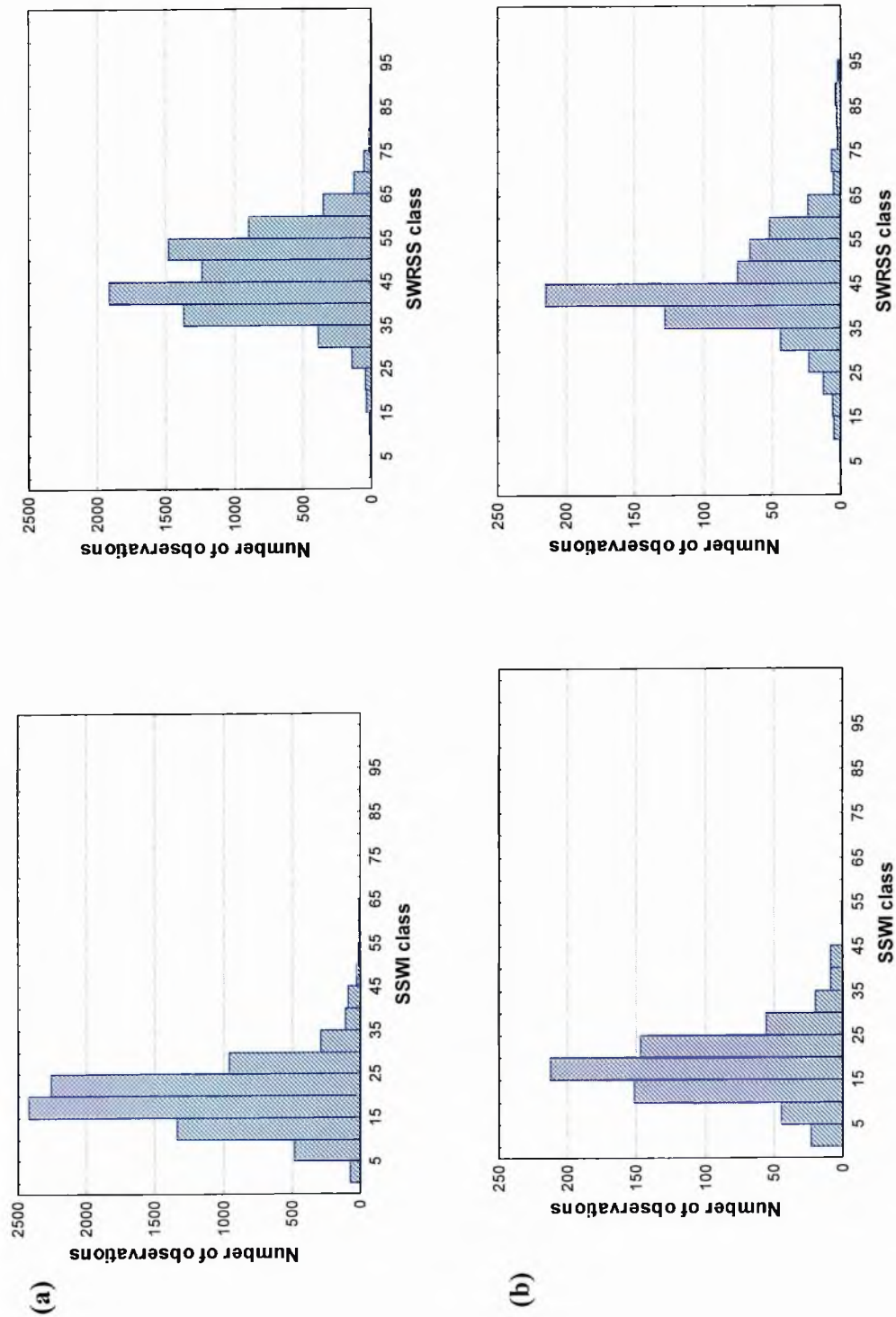


Figure 6-7 Histograms of the SSWI and SWRSS for a 50 m grid size for (a) The study area greater than 3° slope (b) The areas in the representative catchments greater than 3° slope

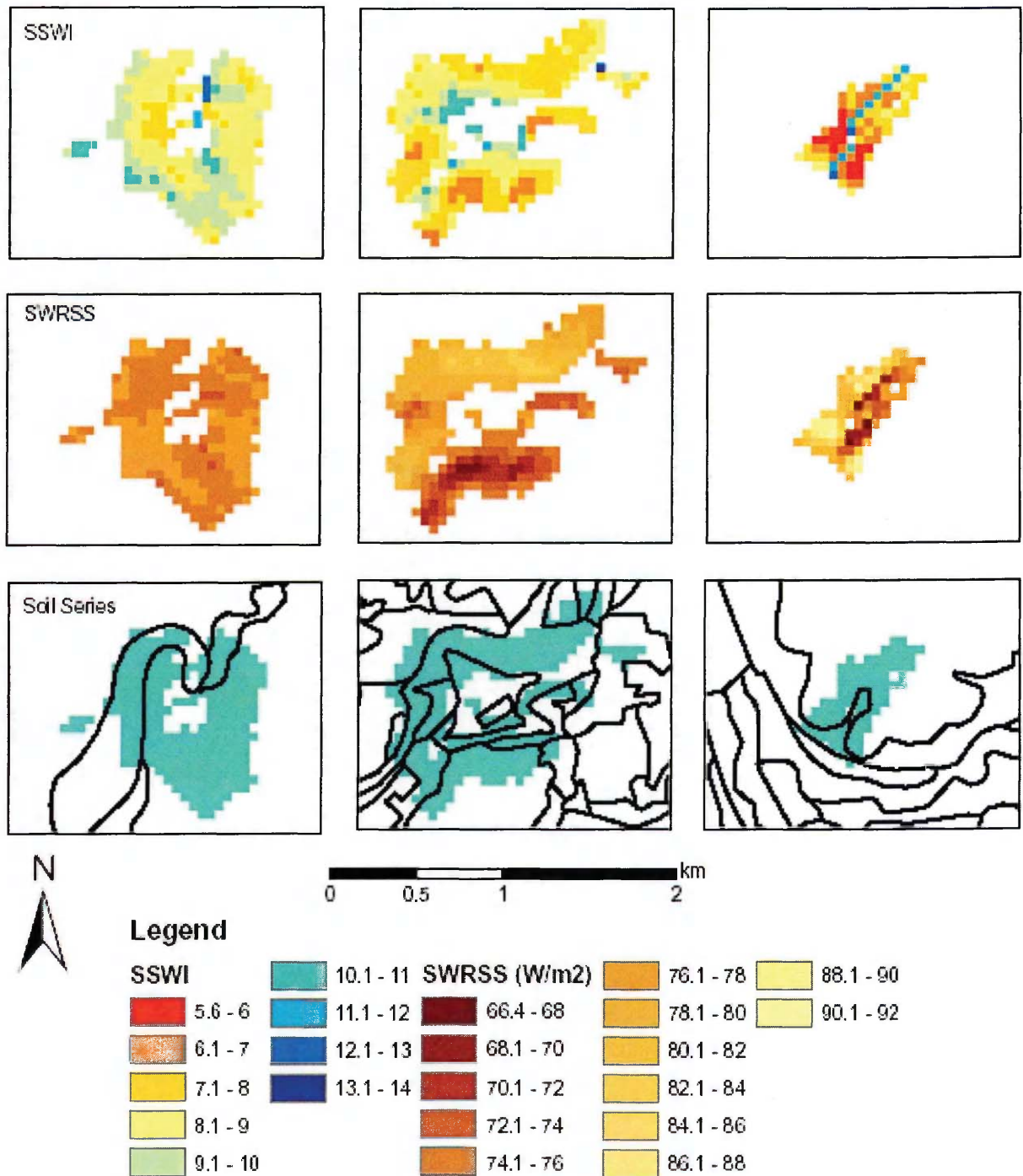


Figure 6-8 Indices and soil series boundaries for the three representative catchments.

6.4 STAMINA runs for representative areas

The STAMINA index and physically based (Version 1.8) models were run for the areas in the catchments selected with slopes greater than 3° (Figure 6.8). The chosen crop was winter wheat and the 1:25,000 soil map was used as an input. The model was run on a 50 m DTM grid. The model was run for 2002 to 2004 and the results from 2003 and 2004 were analysed (Figure 6-9). The meteorological station data were those from the base station in the experimental catchment, but with an added time series from Woburn for 2002 to the start of the recording in the catchment in March 2003. The 2002-2003 growing season was included in the model as doing this improves the initial soil moisture content for the period of interest. The initialisation of the soil water content is shown to be important in predicting soil moisture in the soil hydrological part of the model (Noilhan and Planton, 1989).

6.4.1 Results for running the model for representative areas

Figure 6-9 shows the mapped results for yield for the representative catchments for areas greater than 3° slope. Wilcoxon Matched Pairs analysis showed that the populations of yield from the index and physically based model were statistically different (Figure 6-10). The mapped yield results, however, show similar patterns, especially for the second and third catchments. This is highlighted when the area is divided on a threshold of 6000 kg/ha. Figure 6-11 shows that the same areas in each of the three catchments would be associated as high risk (Russell and Wilson, 1994) in 2004. There was also a statistically significant relationship between the results from the two versions of the model (Figure 6-12). The results for 2003 show crop failure for all catchments for both versions of the model. The patterns seen spatially are more varied between the two model versions. It should be noted that the version of the model used in this analysis will fail to produce reliable yield estimates in extremely wet and dry conditions (Rana and Ferrera, Personal Communication). 2003 was an exceptionally dry year with less than 70% of the long term average rainfall and a total August rainfall of less than 20mm. The predicted yields for 2003 cannot therefore be relied on and the results are therefore not included in the analysis.

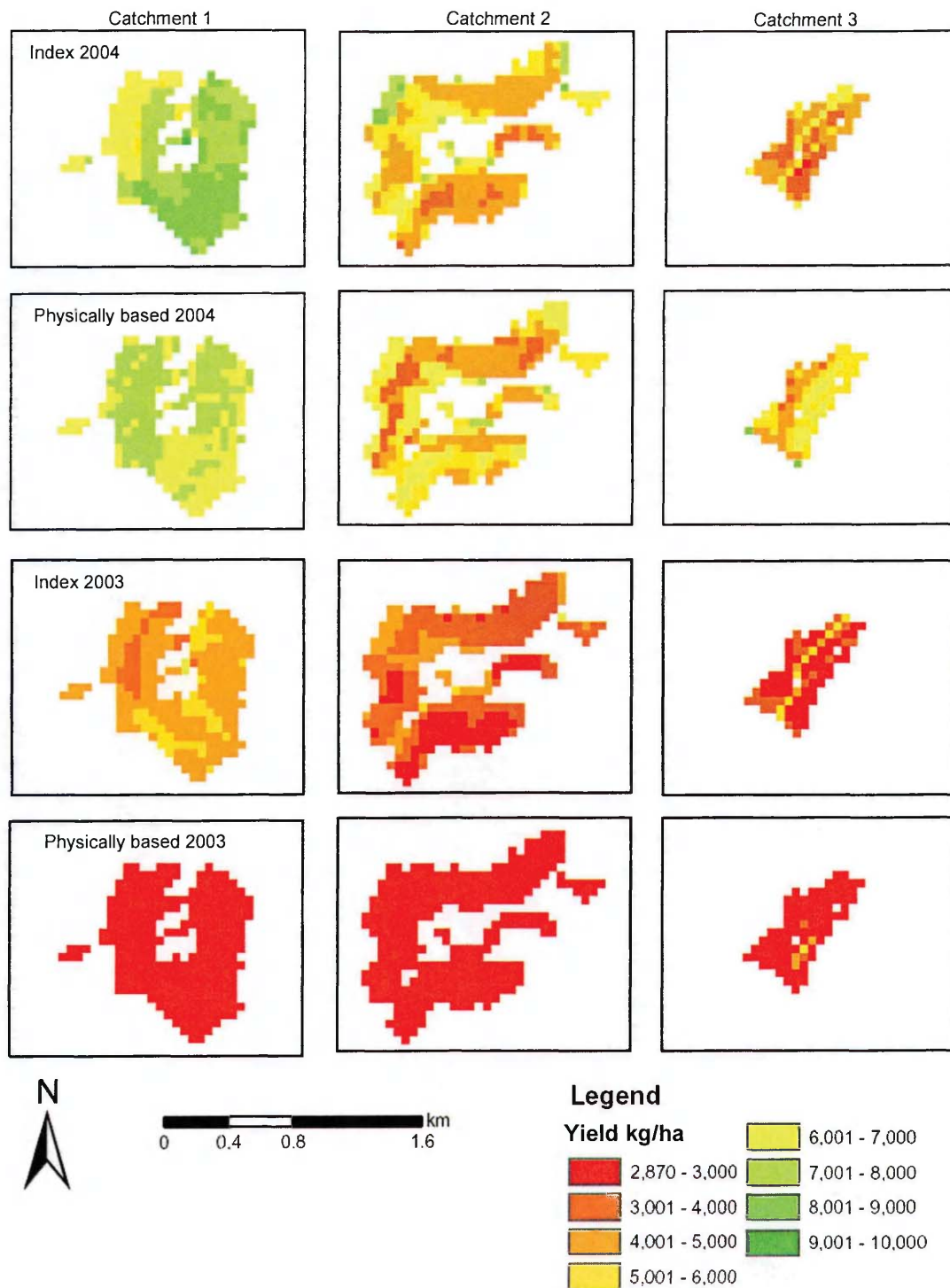


Figure 6-9 Modelled yield for the Physically based and Index versions of the STAMINA model for the 3 representative catchments for 2003 and 2004

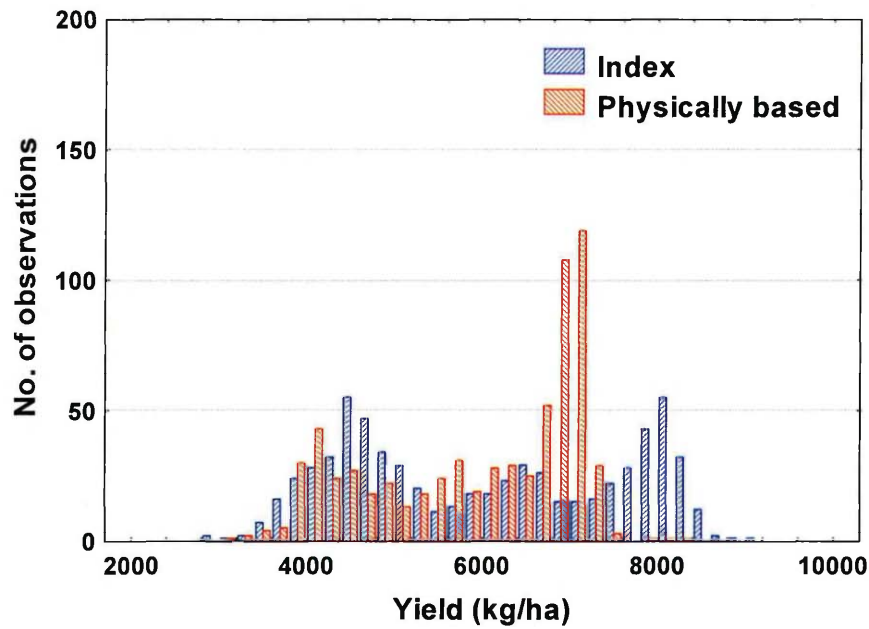


Figure 6-10 Histograms of yield (kg/ha) from the three representative catchments for the physically based and index based approaches to the STAMINA model

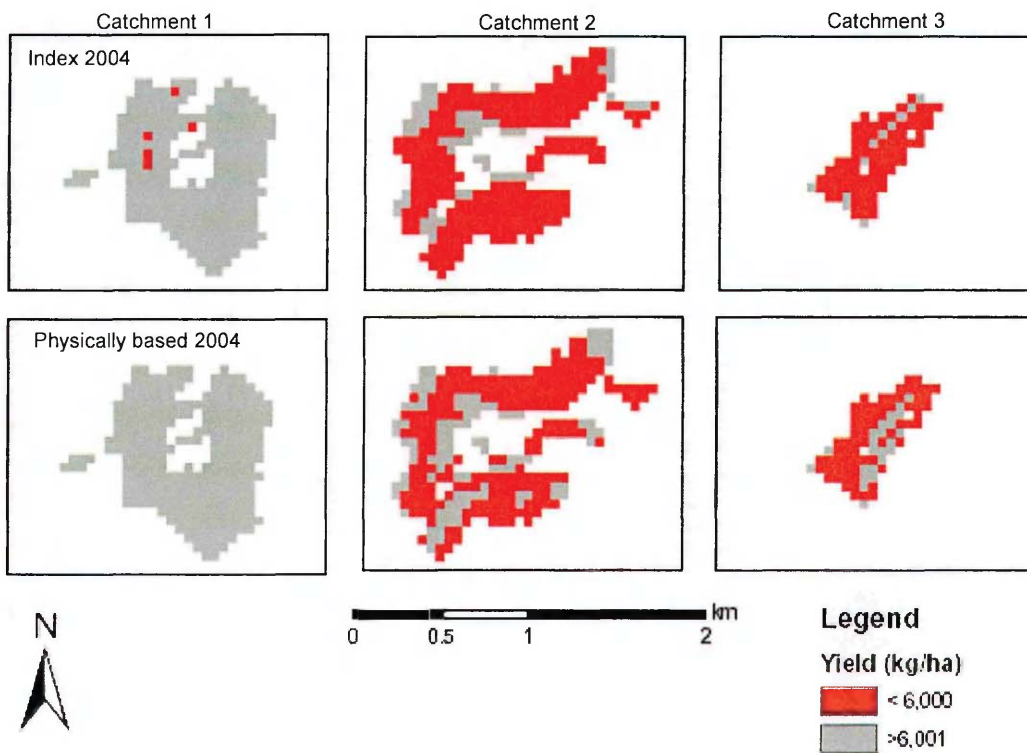


Figure 6-11 Modelled yield for the Physically based and Index versions of the STAMINA model for the three representative catchments for 2004 showing areas with above and below 6000 kg/ha

6.5 Regression approach

6.5.1 Results of the regression

The regression approach is demonstrated with the results from the physically based and the index model. The scatter plot of the results in 2004 suggested that there was a linear relationship (Figure 6-12a). The regression line has a positive slope, significantly different from zero and an r^2 of 0.5. The regression equation is:

$$\text{RegressionEstimate} = 0.53 * \text{Index} + 2780$$

When this was applied to the areas greater than 3° slope in the study area several characteristics were noted:

- The same patterns of yield are seen in the predicted yield in both regressed and index model;
- The regressed model has a smaller range of yield;
- The areas on the ridge with the heavier clay soils are most affected by the application of the regression equation. The modelled yield in these areas is reduced by up to 2t/ha.

Further analysis showed that the points fell into two groups, the lower yields less than 6000 kg/ha in the index model and those greater than 6000 kg/ha (Figure 6-12). These groups are statistically significantly different. These two groups appear to correspond to sandy soils and heavier soils with higher clay content respectively (Figure 6-10b). Furthermore each soil appears to respond differently in the two versions of the model. For example the Warden and Cottenham series show similar predicted yields in the index version of the model, where as they show different yields in the physically based version of the model (Figure 6-12). Figure 6-13 shows the results of applying the regression equation to the areas greater than 3° slope in the 10 km² study area. The same patterns can be seen in the landscape before and after the regression equation is applied. It can also be seen from the difference images that the application of the regression equation affects individual taxonomic soil units differently (Figure 6-13).

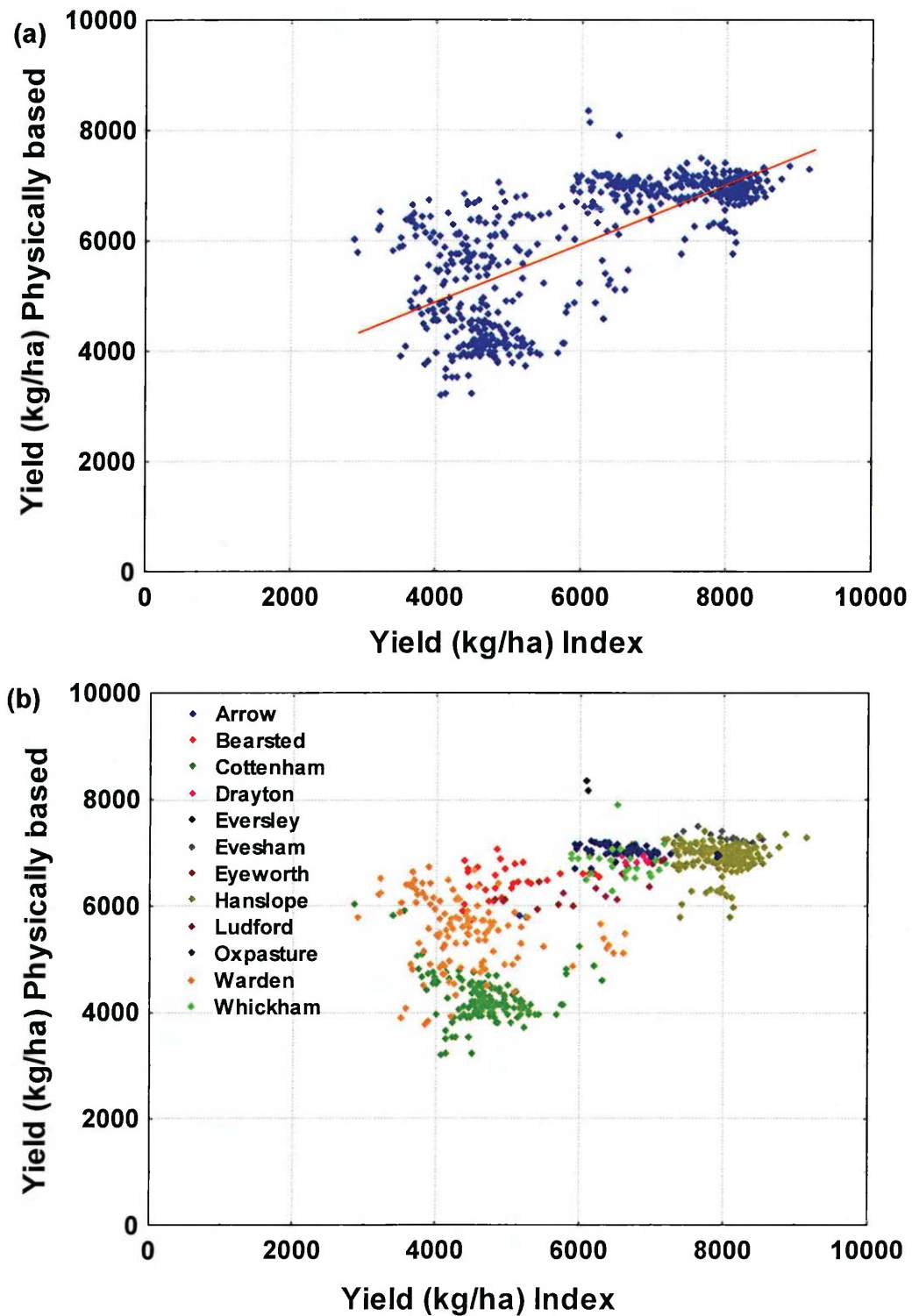
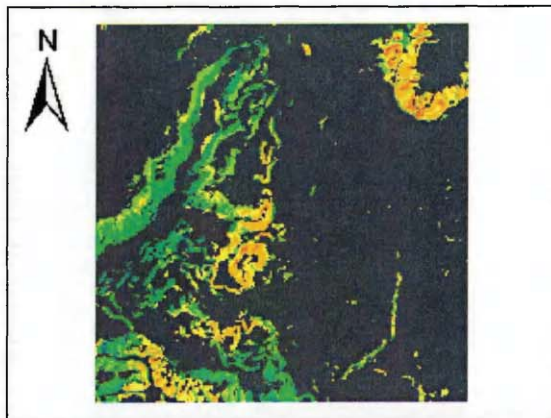
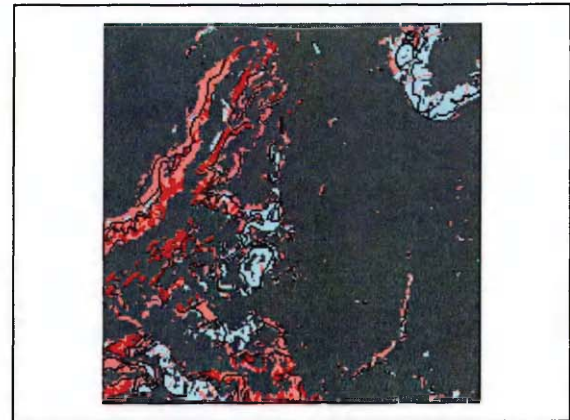


Figure 6-12 Yield in the physically based and index based models for 2004 (a) Shows the regression equation (b) shows the groupings of soil series in the two approaches

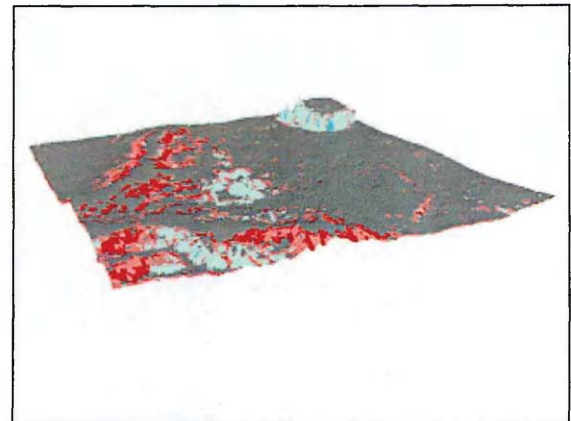
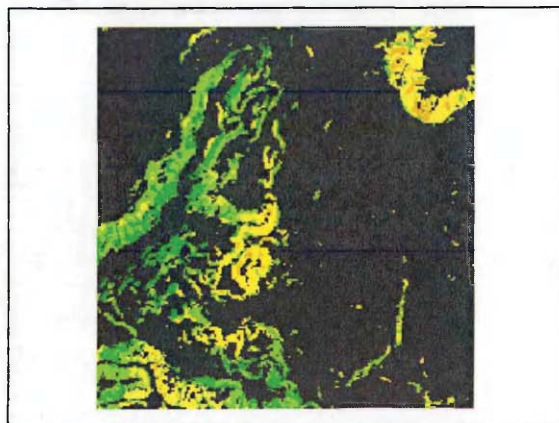
Index



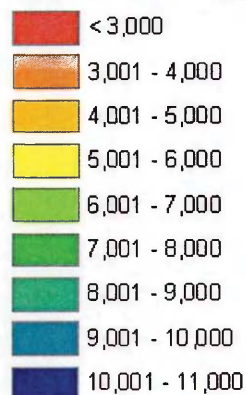
Difference (Regressed - Index)



Regressed



Modelled Yield [kg/ha]



Regressed - Index [kg/ha]



Figure 6-13 The yield for 2004 using the Index based STAMINA model and the regression estimate. The Difference images show the difference in yield between the Index and the regression estimate and hoe these relate to the soil boundaries (Top) and Elevation (Bottom)

6.6 Drivers in the model

In order to determine the drivers in the model it was necessary to create simple regression models between the predicted yield from the model and terrain indices and taxonomic soil units input into the model. Regression models were produced using the yield results in both the physically based and index model to investigate the key drivers in the model. The independent variables were soil series at a 1:25,000 scale and the SSWI and SWRSS, used to distribute rainfall and solar radiation respectively in the index model. The results show that most, over 80%, of the variation in both the physically based and index models is explained by soil series. Very little additional variation is explained by adding terrain variables to the soil series (Figure 6-14). The indices used in the index model parameterisation explain higher proportions of the variation than in the physically based approach. In the index based approach more of the variation is explained by the SSWI compared to the SWRSS. A reason for this could be that the SSWI shows a much higher variation across the study area than the SWRSS.

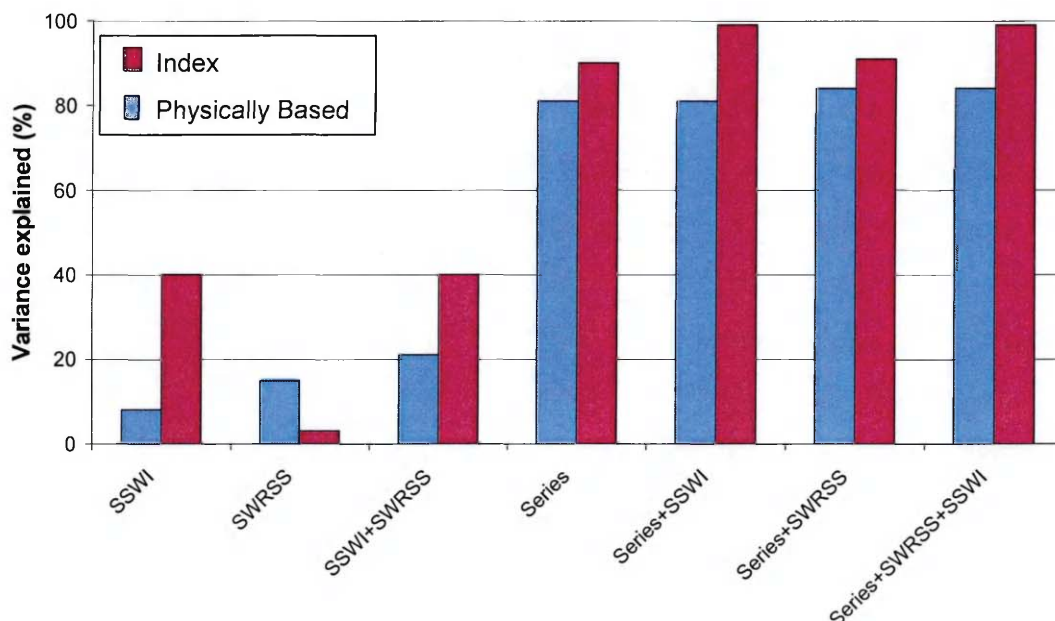


Figure 6-14 Variance explained by SSWI and SWRSS and Soil Series at 1:25:000 scale in the output yields predicted by the Index and Physically based STAMINA model.

6.7 Discussion

The physically based STAMINA model and index based approach show changing responses in soil series with differing soil properties. Figure 6-12 showed several characteristics of these responses. Both versions of the model show the same split at 6000 kg/ha with soils above this value being the soils with increasing clay contents. Furthermore the two versions of the model appeared to converge to a point at which the index based model showed an increasingly linear correlation with the physically based approach, although still slightly over predicting yield values. This occurs with soils that show increasing water retention and therefore have greater water availability for crop growth.

An investigation into the split of soil series in the index and physically based model showed that the variations showed no observable link to the location of the soils in the landscape. One possible explanation is that two different approaches are used to model the soil hydrology in the physically based and index based approaches respectively. The physically based approach is designed to use the ISBA method (Noilhan and Planton, 1989). It assumes a two layer soil profile where as the cascading soil hydrology module splits the soils into 50 mm layers. The physically based approach averages soil properties over the second soil layer where as each of the layers in the cascading approach has soil attributes consistent with its depth in the profile. The physically based version of the model also has the option of using the cascading approach. This was not tested in this research due to issues with the model development over the course of this thesis.

Further analysis showed that the Warden soils showed an increase in organic carbon in the surface compared to the Cottenham series. This is suggested as the reason for the increased yield in this series, due to increased water retention. It is thought that this characteristic is of greater significance, in physically based model, when the drainage is modelled using the ISBA soil hydrology module than in the index based approach which uses the cascading soil hydrology module.

The Hanslope and Oxpasture series are thought to be distinguished in the index model using the cascading hydrology module as they differ in their depth to clay - Hanslope has a

shallower depth to clay than Oxpasture. The difference between these series is thought to become less significant as the soil properties are averaged over from 10 mm to 1 m and hence they are not distinguished in yield predicted in the physically based approach. The finding that the difference in the model response is linked to soil properties and the modelled soil water balance is consistent with the finding that over 80% of the variations in the model are driven by taxonomic soil units.

Further analysis of the model response is required to validate these hypotheses. These need to be linked to yield mapping and a comparison of the predicted and measured drainage using the results from the soil moisture profile measurements. In addition the cascading soil water module needs to be run for the physically based approach and a three way comparison carried out between the physically based approach using the ISBA soil hydrology module, the physically based approach using the cascading hydrology module and the index based approach which can only use the cascading hydrology module. This was not possible in this study due to more general changes to the model formulation, during the course of the project, by other members of the STAMINA project team and the time taken to run the model for each test.

CAS is a useful tool for visualising spatially areas of the landscape that may be represented by smaller areas within a study area. Further investigation needs to be carried out in order to determine the most effective search radius to be used. The CDI index seems quite stable, giving similar results when run for areas above 3° slope and using the entire catchment as a reference area.

The results outlined in this chapter suggest that the STAMINA model may need validating in any specific region where it is to be used. Also caution needs to be exercised if the model is applied to extremely dry years. The results of the General Linear Models developed for the yield outputs (Figure 6-14), show that a combination of the calculated SWRSS, SSWI and a soil map, may be sufficient in highlighting areas of specific concern for low yields

It appears that a regression equation may only be valid on a year by year basis. It is therefore suggested that it may not be an efficient use of time and resources. The index model and physically based approaches seem to highlight the same areas which may be

subject to low yields. An alternative approach to a regression model may therefore be to run the index model first, using this to highlight the areas of interest. If more specific yield data is required the calibrated physically based model can then be run as a second stage for these specific areas.

Further analysis is required to investigate the relationship between yield and soil series (Figure 6-12). This would require examining the results from the crop water stress index generated by the STAMINA model. This could be partly achieved by running the model on a 50 m grid for Stone Hill and Church Meadow using the 1:10,000 scale soil maps which are available. The measurements from the soil moisture access tubes could then be compared to the soil moisture predictions from the model. Ideally this analysis should then be compared to distributed yield results in the field. This would enable validation of both the intermediate outputs of the model and the final yield predictions.

The importance of soil series as a driver in the models requires specific sensitivity analysis. This is because the scale of soil map available for this study, 1:25,000, is much more detailed than the scale of soil map available at a national level, 1:250,000. This analysis is presented in chapter 8. Further analysis was carried out on the sensitivity of the model inputs to grid size. The sensitivity analysis outlined in chapter 8 assesses the loss of information on terrain features caused by increasing the grid size and how this affects the yield output in the index model.

Major results

The key results from this chapter are:

- CAS (Behrens, unpublished) is a useful tool for selecting representative areas of the landscape;
- The index and physically based approaches highlight similar area of the landscape which may be prone to low yields;
- The major driver of crop yields in both versions of the model is soil series;
- Further analysis needs to be carried out in order to validate the yield predictions in a variety of soil series for both versions of the model.

The analysis in this chapter suggests that if a broad approximation of areas of low yield is required then the index model may satisfy this requirement. Changes in the soil hydrology part of the model require further investigation. Chapter 7 examines changes in the drainage function within the physically based model using the ISBA approach.

7 Sensitivity Analysis to drainage function

Experience with the use of the STAMINA model suggested that the form of the drainage function used in the model would have a significant impact on the results. A series of sensitivity tests were therefore carried out to allow complementary analyses of:

- The **measured and modelled drainage**, using two different drainage functions compared with the results of lysimeter experiments carried out at Cranfield University at Silsoe between 1994 and 1996. These experiments were part of the “Pesticide Mobility: Lysimeter study to validate the relative leaching potential of UK soils” (Brown *et al.*, 1997, Brown *et al.*, 2000);
- The forecast **crop yield distribution in the representative catchments** in the Bedfordshire study area as a result of using the two drainage functions.

The assessment of the relative performance of the two drainage functions was carried out as part of the ongoing development of the STAMINA model. This analysis provided the opportunity to compare the predicted yields for simulations that change part of the hydrology module whilst using the energy balance approach. The two drainage functions tested here were selected by members of the STAMINA project team. From these results and those outlined in Chapter 6 there is a discussion as to the relative importance of different aspects of the model in determining the yield distribution.

7.1 Drainage functions used in the STAMINA model

The physically based approach was tested using two drainage equations. The first was a method (Saturated Water Content drainage function (SWC)) (Equation 7-1) based the ratio of water in the second layer of the profile to the saturated water content and the soil saturated conductivity (Noilhan and Planton, 1989).

$$Dr = \kappa_s \left\{ \frac{WC_2}{WC_{sat}} \right\}^{2b+3} \quad \text{Equation 7-1}$$

Where:

Dr – Drainage from the soil profile (mm);

WC₂ – Water content in the second layer of the modelled profile (m³m⁻³);

WC_{sat} – Water content at saturation (m³m⁻³);

b – constant set equal to 2 (Slope of the soil water retention curve in logarithmic space);

κ_s – Saturated hydraulic conductivity (mmd⁻¹).

In this pedo-transfer function the drainage is increased as the water content is increased above saturation and the rate of drainage is determined by the saturated hydraulic conductivity of the soil.

In the second method (Equation 7.2) (FC drainage function) the drainage has a maximum value of the effective rainfall, when the soil is above field capacity. The drainage is zero when the soil is at or below field capacity. This is the drainage function used in STAMINA version 1.8, the version of the model used in this thesis.

$$\begin{aligned} Dr &= R_{EF} - d_2 \text{Max}(0, WC_{FC} - WC_{d2}) \\ \text{Drainage} &= \text{Max}(0, Dr) \end{aligned} \quad \text{Equation 7-2}$$

Where:

R_{EF} – Effective Rainfall (mm);

Dr – Drainage (mm);

d₂ – Depth of the second layer in the modelled profile (mm);

WC_{d2} – Water content in the second layer of the modelled profile (m³m⁻³);

WC_{FC} – Water content at field capacity (m³m⁻³).

7.2 The Lysimeter Study

7.2.1 Method

The relative performance of the two drainage functions was compared using observed data using results from Lysimeter experiments from a study carried out at Cranfield University at Silsoe in 1994-1996 (Brown *et al.*, 1997). The results from this study, including meteorological data for this time period, were compiled. The study tested five soil series with different drainage characteristics:

- **Enbourne** – Cracking clay alluvium;
- **Cuckney** – Unstructured freely draining sand;
- **Sonning** – Free draining shallow loam over gravel;
- **Ludford** – Deep weakly structured loam;
- **Isleham** – Shallow peat over freely draining sand.

Three of these soils, **Ludford**, **Cuckney** and **Sonning** are found in the 1:25,000 soil map of the 10 km study area (Wright, 1987). **Ludford** and **Cuckney** are also found in the Stone Hill and Church Meadow fields when mapped at 1:10,000 scale (Burton, 2003).

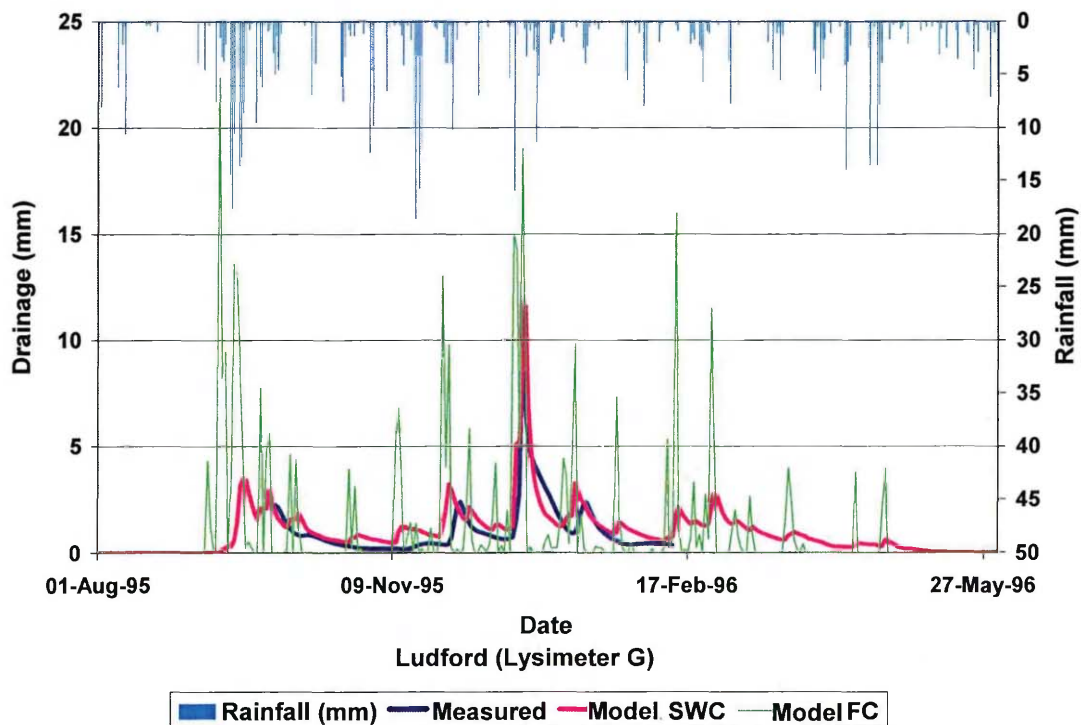
The STAMINA model simulated the period from 1st July 1995 to 1st November 1996. The input of hourly meteorological data was from a weather station on the lysimeter site and each of the lysimeters was treated as the reference point within the model.

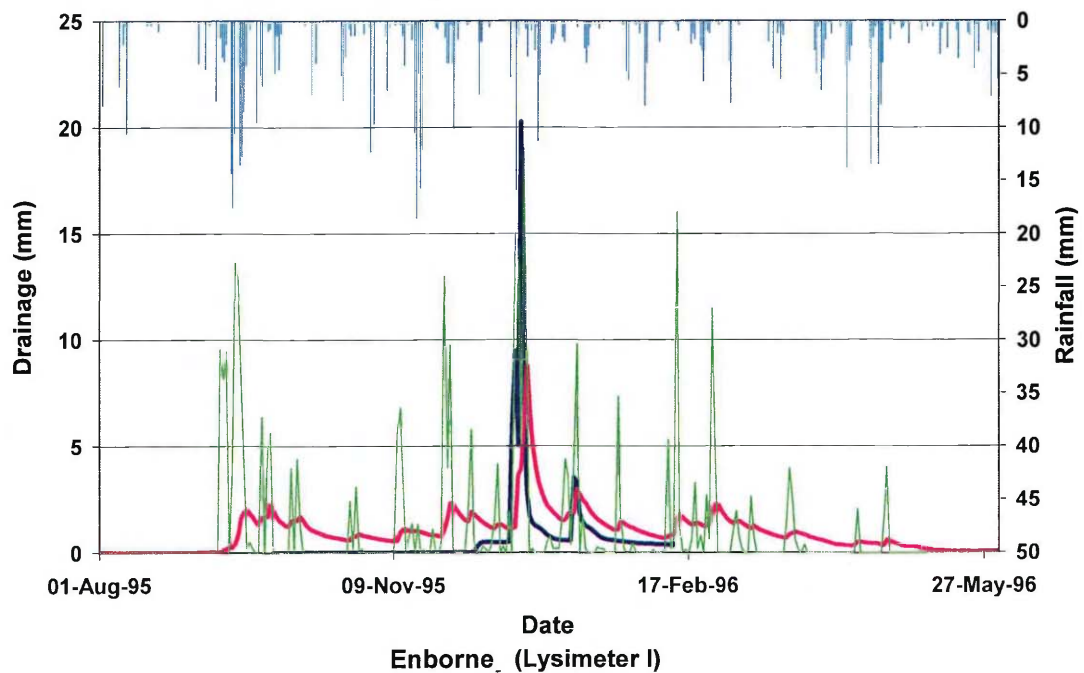
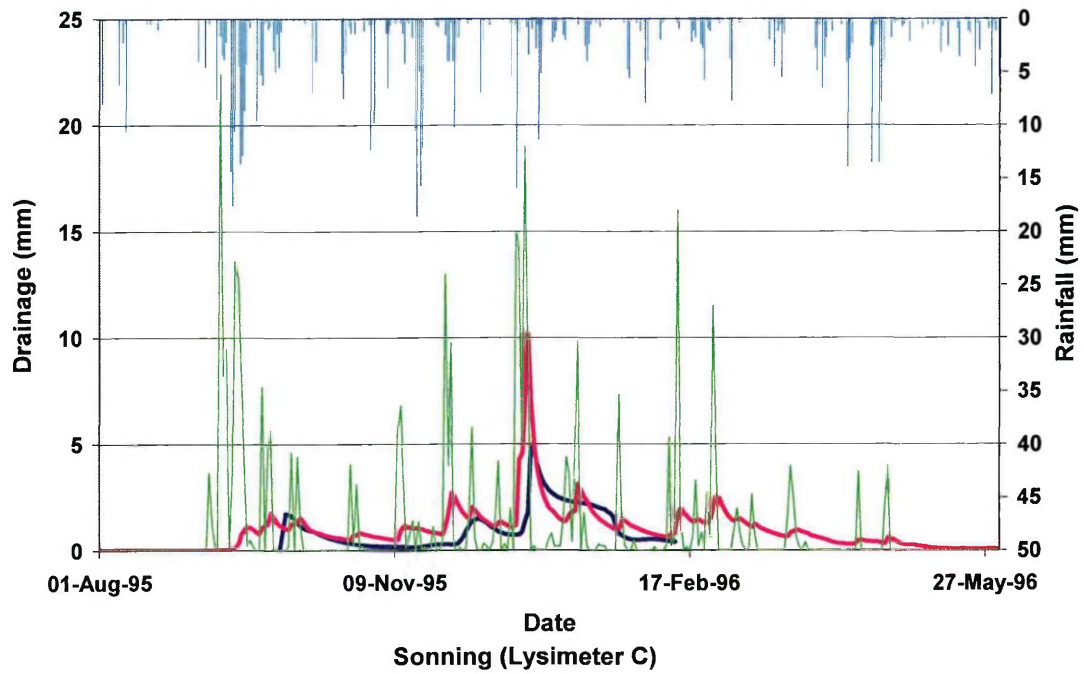
7.2.2 Results

The measured and modelled drainage for the physically based SWC drainage model showed very similar patterns and the drainage was predicted well for the **Cuckney** (free draining sand) and **Ludford** (weakly structured loam) (Figure 7-1). The worst drainage predictions were found in the **Isleham** (Peat over sand) and **Enborne** (cracking clay) (Figure 7-1). The poor results in the **Enborne** series can be explained by further investigation outlined in the Lysimeter study. Dye tracing techniques suggested that the dominant flow in this series is bypass flow. However this flow is not modelled as part of the

STAMINA model, which would explain the more peaky and faster response of the measured drainage compared to the model results. The **Isleham** series is a peat and therefore has a high organic matter content, which the pedotransfer functions used in the model are not developed for.

When compared to the measured drainage in the lysimeters (Figure 7-2) the FC drainage function shows a much higher RMSE than the SWC drainage function. It also has a much more peaky time series (Figure 7-1). On the basis of these results there was a case for changing the drainage function in the STAMINA model, from the FC function to the SWC one. In order to further validate such a change an analysis of the yield predictions for the representative catchments in the study area was required. The SWC drainage function gives an RMSE of 80-100% when compared to the measured data. This is contrasted with an RMSE of around 300% using the FC drainage function (ignoring the peat and cracking clay soils). The fit of the SWC drainage function can be improved upon by optimisation of the parameter “b” (Equation 7-1). The analysis undertaken here, however was to demonstrate the sensitivity of the STAMINA model yield outputs to two different drainage equations and highlight problems with using the FC drainage function..





■ Rainfall (mm) ■ Measured ■ Model SWC ■ Model FC

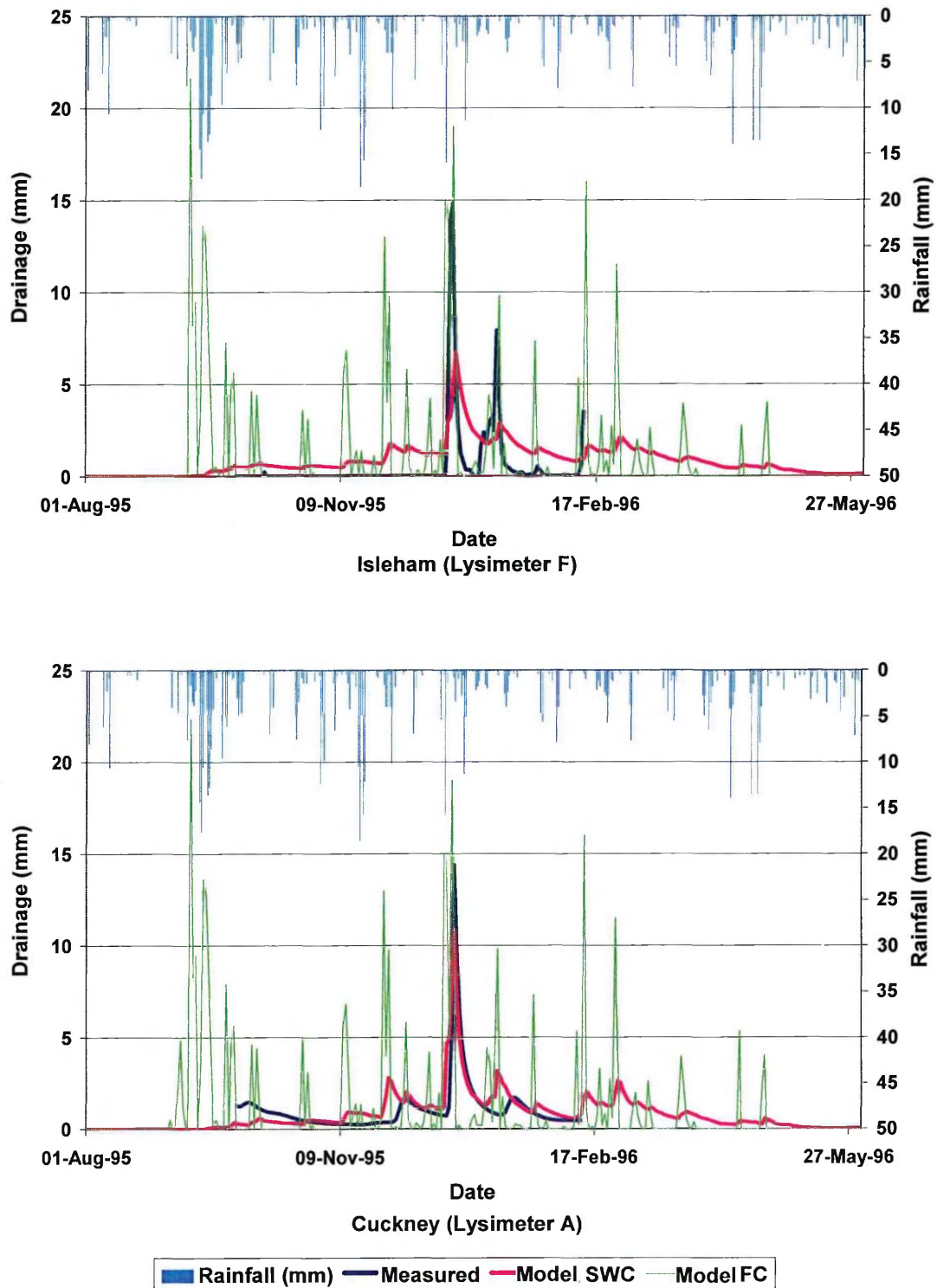


Figure 7-1 Rainfall and drainage measured at each of the five lysimeters during the lysimeter study at Silsoe (Brown *et al.*, 1997) compared to the drainage modelled in the STAMINA model using the SWC and FC drainage functions

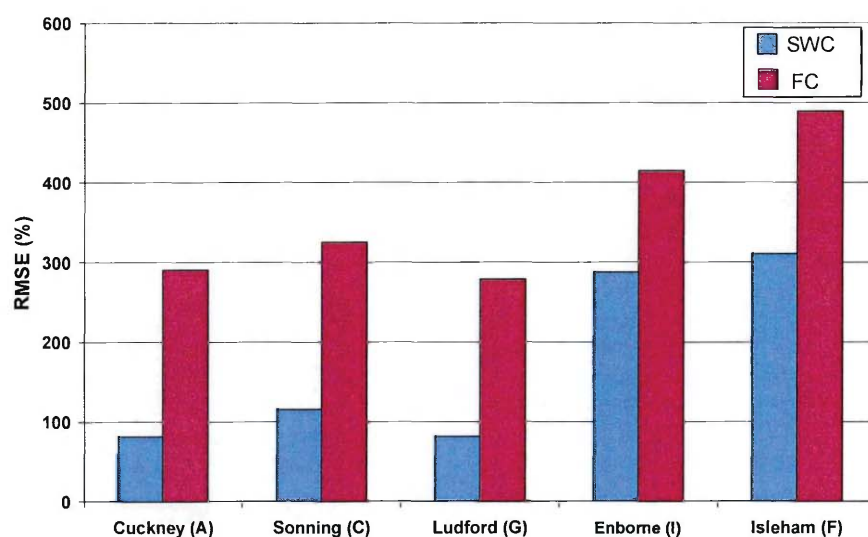


Figure 7-2 Root Mean Square Error (RMSE) between the measured and modelled drainage using SWC and FC drainage functions in the STAMINA model

7.3 Analysis of predicted yields from representative areas

7.3.1 Method

The physically based STAMINA model was run for two drainage functions for the areas with slope greater than 3° in the selected catchments. Note :*The same input parameters were used as for the comparison between the physically based and index based approaches as described in Chapter 6.*

7.3.2 Results

The analysis showed that the yield data from the physically based SWC drainage function belonged to a different population to the physically based FC drainage function. The physically based SWC model predicted a smaller range of yields, which are generally higher than those in the physically based FC model (Figure 7-3 and 7-4) Wilcoxon Matched Pairs analysis showed that the two populations of yield obtained using the FC and SWC drainage functions in the physically based version of the model were statistically different

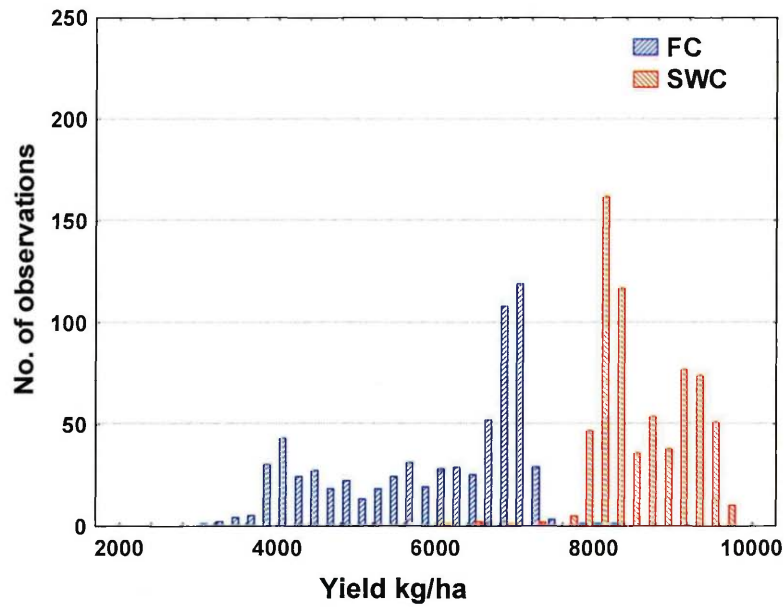


Figure 7-3 Yield distributions for the representative catchments in the study area using the SWC and FC drainage functions in the STAMINA model

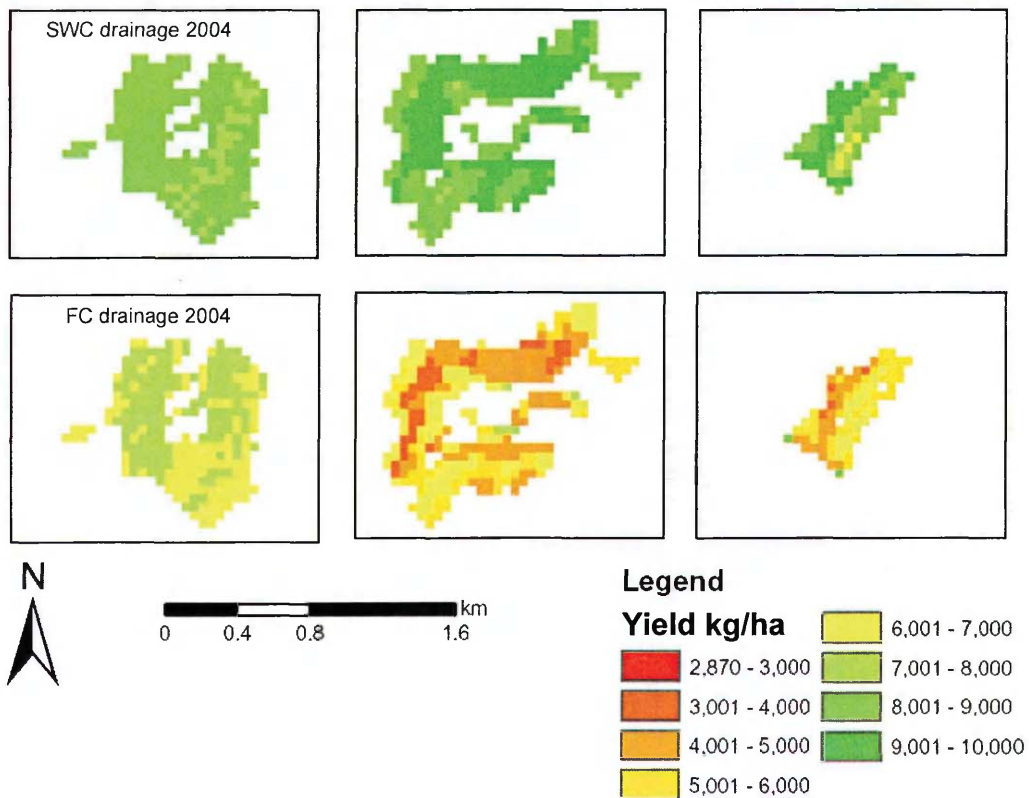


Figure 7-4 Yield maps for the representative catchments in the study area using the SWC and FC drainage functions in the STAMINA model

7.4 Discussion

The predicted yields using the FC drainage function showed a reverse response for sand and clay soils compared to the SWC drainage function. The clay soils in catchment 1 showed higher yields than the more sandy soils in catchment 2, using the FC drainage function and lower yields than the more sandy soils using the SWC drainage function. Investigations into the model response for the lysimeters suggest that this response is driven by crop water stress. The soil moisture time series, (Figure 7-5) results for the cracking clay, Enborne, were compared to the freely draining sand, Cuckney.

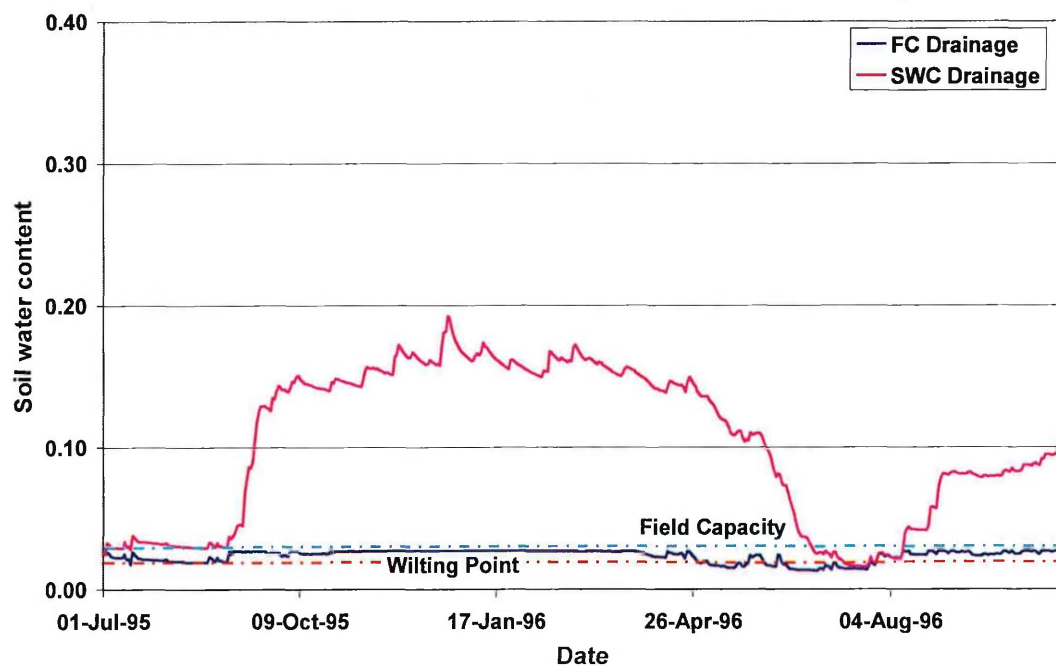
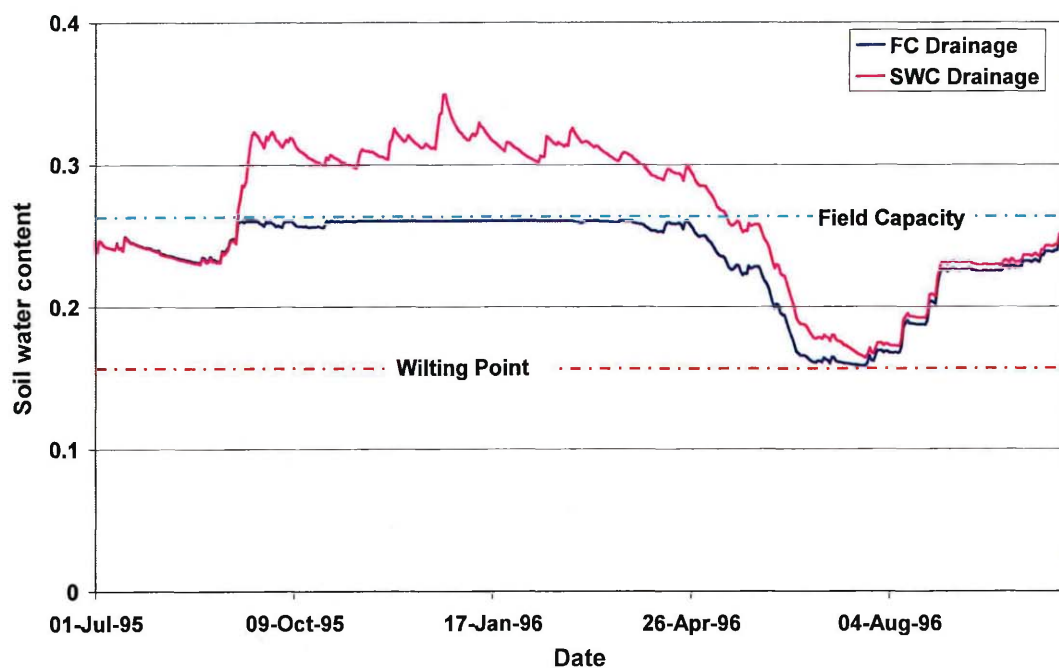


Figure 7-5 (a) Modelled soil water content for the (b) Modelled water content for the Enbourne Lysimeter. Using the SWC and FC drainage functions. The field capacity and wilting point shown are the values calculated by HYPRES pedotransfer function in the STAMINA model.

The available water for plant growth was that between field capacity and wilting point as calculated from soil texture characteristics using the HYPRES pedo-transfer function (Rana, 2006 Personal Communication). The predicted FC and WP in the model appeared to be very low, particularly in the simulation for the Cuckney Lysimeter (Figure 7-5). The values calculated by the HYPRES pedotransfer function in the model were compared to the measured values for the soil series (Table 7-1). The available water content for the cockney lysimeter is 1% vol/vol. This compares with a measured value of 7% vol/vol. The value of available water content in the Enbourne is similarly underestimated, 10% vol/vol compared to a measured value of 23% vol/vol. This suggests that whichever drainage function is used the STAMINA model will under predict the actual yield of the crop. There is a further problem with the FC drainage function. This is that it allows the water content in the soil to drop below WP. This leads, as expected, to crop failure in the predicted yield for the Cuckney lysimeter.

Table 7-1 Predicted and measured water contents

Soil Series	Variable	HYPRES-Predicted water content (% vol/vol)	Measured water content (% vol/vol)
Cuckney	Saturated Water Content	37	41
	Field Capacity	3	10
	Wilting Point	2	3
Enbourne	Saturated Water Content	49	49
	Field Capacity	26	40
	Wilting Point	16	17

In the representative catchments the overall higher yields in the SWC are thought to be a function of the higher soil moisture recharge potential over the winter months and consequently the slower decrease in soil moisture through the growing season to below the modelled field capacity. This is reflected in the lower Crop Water Stress Index (CWSI) for

the simulation using the SWC drainage function than for the FC drainage function in the lysimeter experiments (Table 7-1). The CWSI is an output of the STAMINA model.

Table 7-2 Crop Water Stress Index (CWSI) calculated from the STAMINA model for the Enborne and Cuckney Lysimeters

Drainage Equation	Soil Series	CWSI
Saturated Water Content	Cuckney (Sand)	0.184
	Enborne (Clay)	0.195
Field Capacity	Cuckney (Sand)	0.314
	Enborne (Clay)	0.228

The CWSI is more similar between the modelled lysimeter results between sandy and clay soils in the SWC function. This is reflected in the more similar yield predictions between the sandy and clay soils. The results from the soil moisture time series from the lysimeter experiments show a longer time where the soil is below the modelled field capacity in the clay, Enborne series, than in the sandy, Cuckney. This appears to be the source of the increased water stress in the Enborne series than in the Cuckney series, inspite of the very low available water in the Cuckney series.

The overall response of the two drainage functions suggests that the yield in the model is most strongly determined by the model's ability to accurately simulate recharge over the winter months. The FC drainage function only allows recharge in the soil profile up to the modelled field capacity, where as the SWC drainage function allows the soil to recharge up to saturated water content.

The predicted yield in the model was found to depend very heavily on the drainage function used in the model. The physically based SWC gives a much improved prediction of the drainage within the soil when compared to the physically based FC drainage function. To determine which of these produces more reliable yield estimates in hilly terrain requires extensive mapping of actual yield in a variety of soils in sloping areas.

Changing the drainage equation changes the population of yield results and leads to very different predicted spatial patterns, which are linked to soil series. In contrast changing the form of the model from the physically based method of distributing the meteorological

parameters with respect to the terrain to an index based method changes the statistical distributions but does not affect relative response of clay and sandy soils and maintains similar patterns of yield in the landscape (Chapter 6). This suggests the drainage function is more important in correctly predicting yield in the model than the method by which the meteorological parameters are distributed in the landscape. It also suggests why soil series are the most important driver in both versions of the model, as it is the soil properties that control the drainage at a point.

Further work in the development of the STAMINA model requires:

- Determination of the properties of the soils that respond differently depending on the drainage function used;
- Extensive yield mapping in hilly terrain to validate these findings and conclude which drainage function is most appropriate for mapping the risk to farming in hilly landscapes;
- Comparison of the model runs for:
 - One soil series over an entire region with distributed meteorological parameters;
 - Non distributed meteorological parameters with spatially variable soils.

The findings outlined here suggest that changing the soils will have a smaller variation than moving to distributed meteorological parameters. This, however, may not be the case in more extreme topography.

7.5 Major results

The key results from this chapter are:

- A change in the drainage function has a larger impact on the yield predictions than changing the micrometeorological module from a physically based approach to an index based one;
- The SWC drainage function gave a better prediction of the pattern of flow in the Lysimeters;
- Further yield mapping in hilly terrain in a variety of field types is required to validate the model.

8 Sensitivity analysis to grid size and soil scale

This chapter presents an assessment of the effects of:

- **Increasing the grid size** of the DTM over which the model is run;
- **Decreasing the resolution of the soil map** used in the model simulations;

on the predictions of yield at a regional extent., in this case the 10 km² study area in Bedfordshire

8.1 Effect of grid size on indices at a regional level

Increasing the Grid Size of a DTM decreases its ability to accurately represent topographic features in the landscape. Grid size also has a substantial impact on the usability of the model to examine changes in yield over large areas. Grid size is an important consideration when applying the index based model at a regional level - at a 50 m grid size the STAMINA index model takes several days to run to provide output for a 10 km² area and the physically based model takes several days to run for a few hundred cells. Hence grid size analysis was applied to the index model to find the maximum grid size at which the model can be run. The SSWI, and SWRSS and Average Air Temperature were analysed for their sensitivity to grid size. Figure 8-1 shows the mean, maximum and minimum values of these parameters at grid sizes of 20 m, 50 m, 100 m, 200 m 500 m and 1 km. As the range of the indices decreases it was expected that the detail in the spatial patterns and the effect of individual topographic features would be lost.

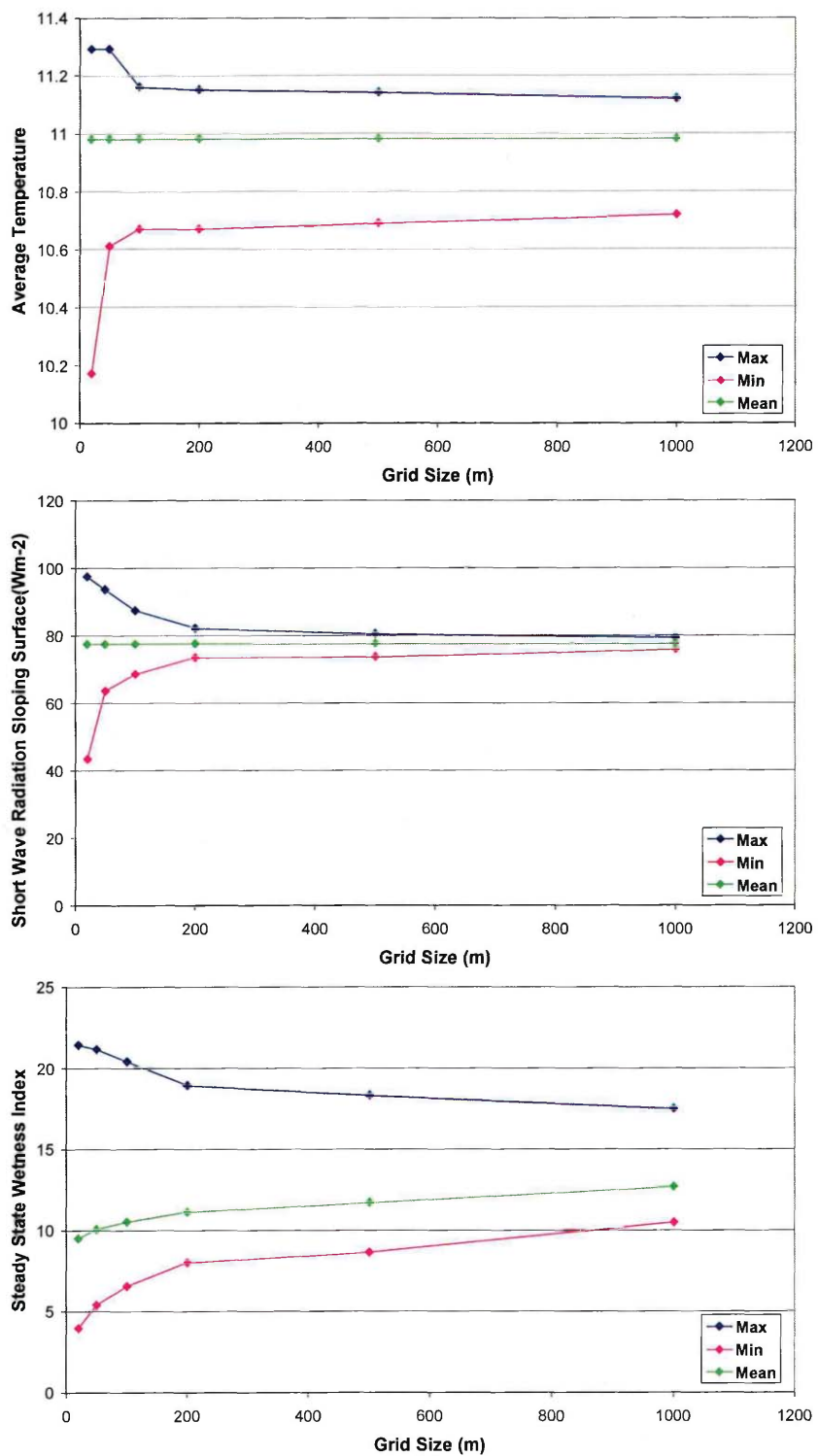


Figure 8-1 Maximum, minimum and mean values of the three indices used in the STAMINA model over the 10 km² study area at increasing DTM grid sizes

The SWRSS lost information most rapidly at grid sizes greater than 20m and by 200m there was very little variation across the study area (Figure 8-1). The SSWI had a much more consistent range up to a grid size of 100 m and then there appeared to be a large reduction in the information contained in the index as the grid size is increased from 100 m to 200 m. In the temperature index most of the variation is lost beyond a grid size of 20 m and the temperature at increased grid sizes showed a constant and very small range (Figure 8-1). In this area the modelled temperature differences are negligible. However this index is still included in the index approach to modelling as in regions with much greater, topographic variation the variations in temperature could potentially be a major driver in the distribution of yield and other indicators output by the STAMINA model.

The topographic indices outlined above were divided by the values at the base meteorological station in order to provide an index by which to distribute the meteorological parameters measured at the base station. The index based on the SSWI was used to distribute rainfall, the index based on SWRSS to distribute radiation and the temperature index to distribute temperature. When the SSWI was divided by the base station value the distribution is shifted towards lower values at 200 m and then the maximum, minimum and mean values are increased at 500 m. It is suggested that this is function of the location of the reference point within the surrounding cells. The same patterns were also seen in the output yield values (Figure 8-3)

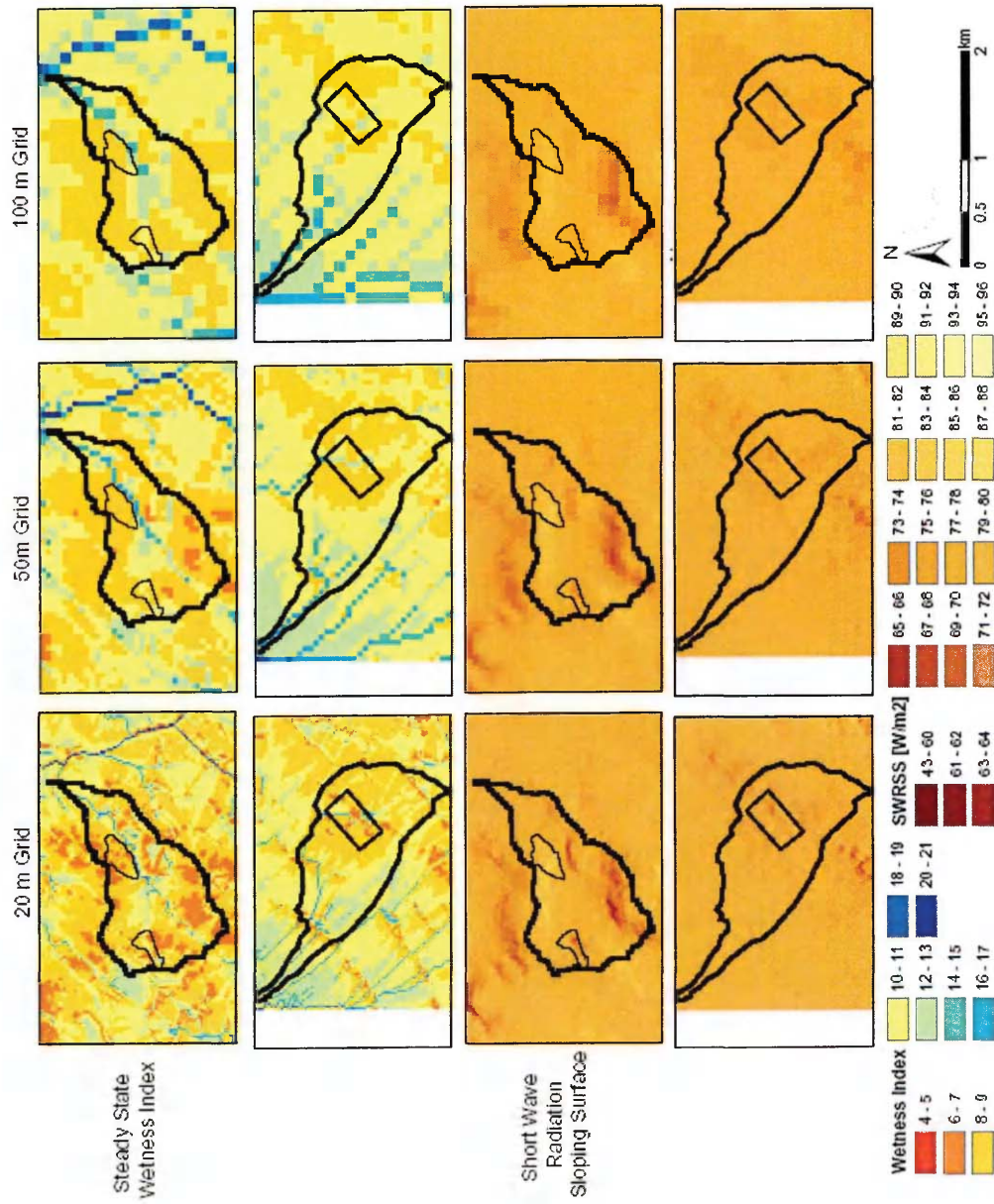


Figure 8-2 SSWI and SWRSS for each of small catchments containing the field sites at grid sizes from 20 m to 100 m

The spatial distribution of these indices shows clearly the decrease in information and the loss of small topographic features, as the grid size increases (Figure 8-3). This can be seen most clearly in the topographic features associated with the Lower Greensand outcrops in the vicinity of the field sites. The spatial patterns shown in the two field sites show that increasing the grid size up to 100 m most of the patterns related to channels and small shaded areas have disappeared (Figure 8-2).

At a grid size of 20 m the SSWI grid shows a very detailed pattern of channels. The 50 m grid shows a more generalised pattern but still highlights the major channels and features within the experimental fields. The SWRSS shows little change between 20 m grid size and 50 m grid size.

The physically based (STAMINA) model can only be run for a few hundred cells. Therefore for the purposes of analysing the model response and comparing the results of the index and physically based approaches a 50 m grid is the most detailed which the model can be used. It is then suggested that for studying the spatial distribution of yield and other model outputs at a regional level a grid size of 100m may be sufficient in the gently undulating study area.

8.2 Effect of grid size of and input soil resolution on yield variability

The spatial distribution of the yield is seen to lose detail at grid sizes greater than 100m, with the major patterns which follow the terrain being masked at 500m (Figure 8-5). The spatial distribution of yield suggests that a 100 m grid size is sufficient to draw broad conclusions about the regional spatial distribution of yield (Figure 8-5). It should be noted however that these conclusions will be dependant on the topographic characteristics in a given region and will depend on average slope length and the distribution of small scale topographic features.

Changing the scale of the soil map has a different effect on yield in different soil association polygons, depending on the distribution of soils within the polygon. These soils can often have very different properties to those of the dominant series (series used in

modelling) of the association. In the study area the projected yields in the main Ivel river valley tend to decrease as the soil scale becomes increasingly generalised and those to the west of the Till ridge increase.

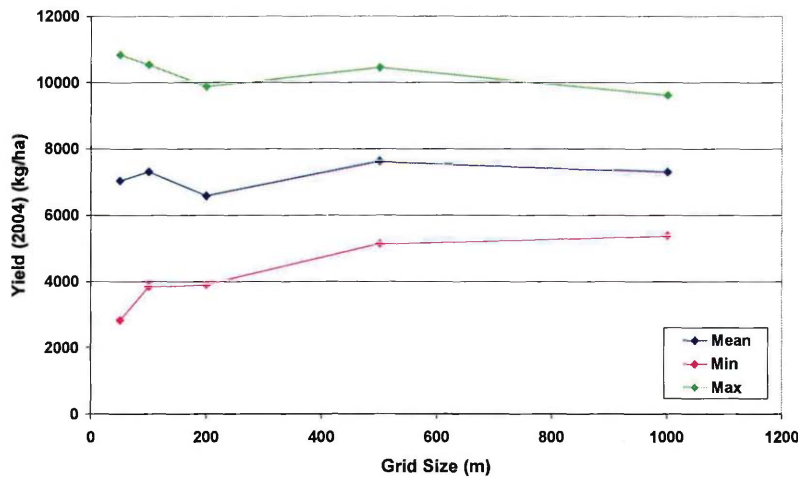


Figure 8-3 Maximum minimum and mean yield values modelled using the Index based STAMINA model for the 10 km² study area at grid sizes from 50 m to 1 km

Analysis of the Root Mean Square Error (RMSE) shows that there is an increase in error when the grid size is increased up to 500 m and then the RMSE does not increase any more to 1000 m (Figure.8-4) The difference in using the 1:250,000 scale soil map compared to using the scale map is equivalent to increasing the grid size in the area to 500 m.

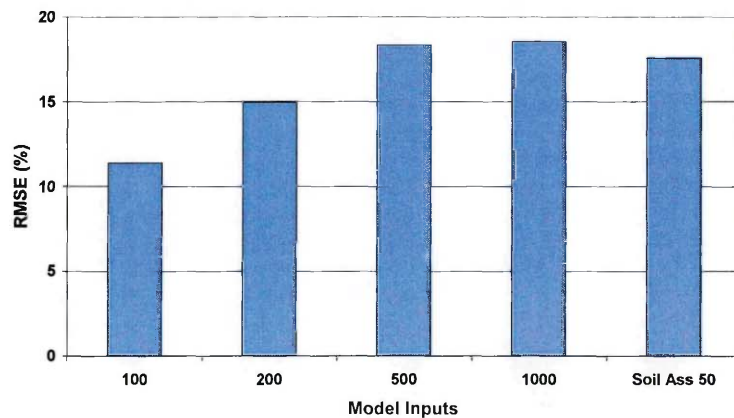


Figure 8-4 Root Mean Square Error (RMSE) between yield modelled at 50m using 1:25,000 scale soil series data and yield modelled at 100 m, 200 m, 500 m and 1km grid sizes using 1:25,000 scale soil series data and at 50 m grid size using 1:250,000 scale soil association data.

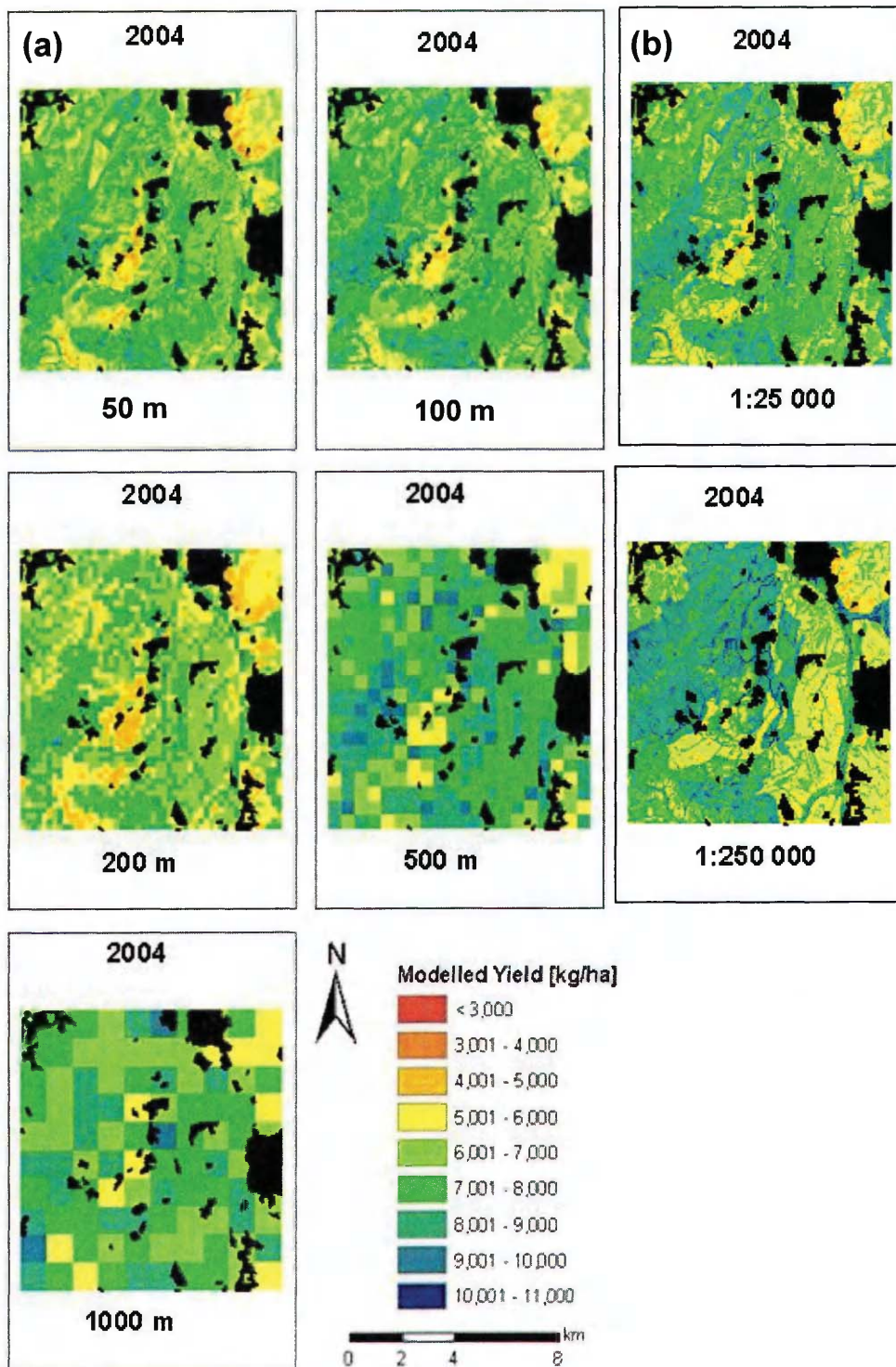


Figure 8-5 Yield maps output from the STAMINA model using (a) Grid sizes 20 m, 100 m, 200 m, 500 m and 1 km and 1:25,000 scale soil series data (b) 50 m grid size and 1:250,000 soil association data

8.3 Discussion

The changes in grid size of the DTM are reflected in the parameters and indices calculated from it. Increasing the grid size of the DTM decreased the maximum and increased the minimum elevations, decreasing the range in the study area. It also decreased the average slope, both on the major catchment watersheds. The combined effect of these had an impact on both the shading on hill slopes and the range of aspects represented. This cumulative effect was reflected in the SWRSS and this would explain the lack of variation in the SWRSS at large grid sizes and the rapid decrease in detail seen in this index.

The minimum values of each of these indices are associated with the most steeply sloping areas and the highest elevations. These are the areas where detail is most rapidly lost with increasing grid size. This affect was seen in the more rapid convergence of the minimum values than for the maximum values, which are primarily associated with the low lying and flatter areas of the landscape.

The patterns seen in these indices will be more accentuated in more steeply sloping terrain. Since the recommended grid size for running the model is less than the 'half length', defined in Chapter 3, it is important to not only calculate this value but also to check the indices for the grid size at which information is lost and therefore areas highlighting low yield become masked in the STAMINA simulation outputs.

The DTM indices in this area appear to suggest the same grid size as appropriate for running the STAMINA model as the output yield. This means that an appropriate grid size for running the model can be determined by calculating, plotting and mapping the three indices required for the model. This is an important consideration in any attempt to apply the STAMINA model at a regional level as this processing takes much less time than running simulations. Furthermore it is not dependant on the time series of meteorological data used in the model.

In the study area the SSWI shows a larger percentage variation than the SWRSS of average temperature. It is also a more major driver of the model results, hence the variation of this index with respect to grid size is the most important when determining the appropriate grid size for running the STAMINA model. In areas of

increased topographic variation the appropriate grid size for running the STAMINA model may change.

The results outlined in this chapter also highlight the importance of the scale of the soil data in driving the reliability of the outputs of the STAMINA model. It is suggested from the results outlined above that there will be significant bias in the results when running the model using 1:250,000 soils data compared to 1:25,000 soils data. In areas of more steeply sloping terrain, soils often have closer link to soil properties. In these areas it is suggested that the addition of terrain data into agricultural modelling may result in more similar patterns in the landscape being observed between increasingly coarse levels of soils data.

As the conclusion of this discussion of the impact of increasing the grid size in the STAMINA model suggests that a grid size of 100m, much less than the 500 m half length calculated for the study area (Horton, 1945) is required to accurately model the yield. This is consistent with the conclusions drawn from hydrological modelling (Zhang and Montgomery, 1994; Beven, 1997), which indicates that processes occurring within the slope are important in the distribution of meteorological parameters in the slope.

Further analysis is needed to ascertain the affects of changing the grid size and soil scale simultaneously. This is expected to show that the grid size can be increased beyond 100 m if soils data is only available at 1:250,000 scale as changing the scale of the soils data has a greater impact on the yield results than changing the grid size of the DTM. . It is recommended that if soil association data at 1:250,000 scale, are to be used in the model local knowledge, of the dominant soil series is used to determine the soil series used in modelling. This is because it has been shown that the national level dominant series does not necessarily correspond to the series mapped at a more detailed scale. (Appendix IV)

The analysis of the results from Chapters 7 and 8 suggests that there are potential problems with some of the functions in the STAMINA model. The model appears to be much more sensitive to a change in the drainage function than to change in the form of the micro-meteorological sub-model (Figure 8-6). The RMSE between changing from the physically based model using the field capacity drainage function

at 50 m and the physically based model using the SWC drainage function is almost three times that of changing from a physically based model using the field capacity drainage function and the index based model (Figure 8-6).

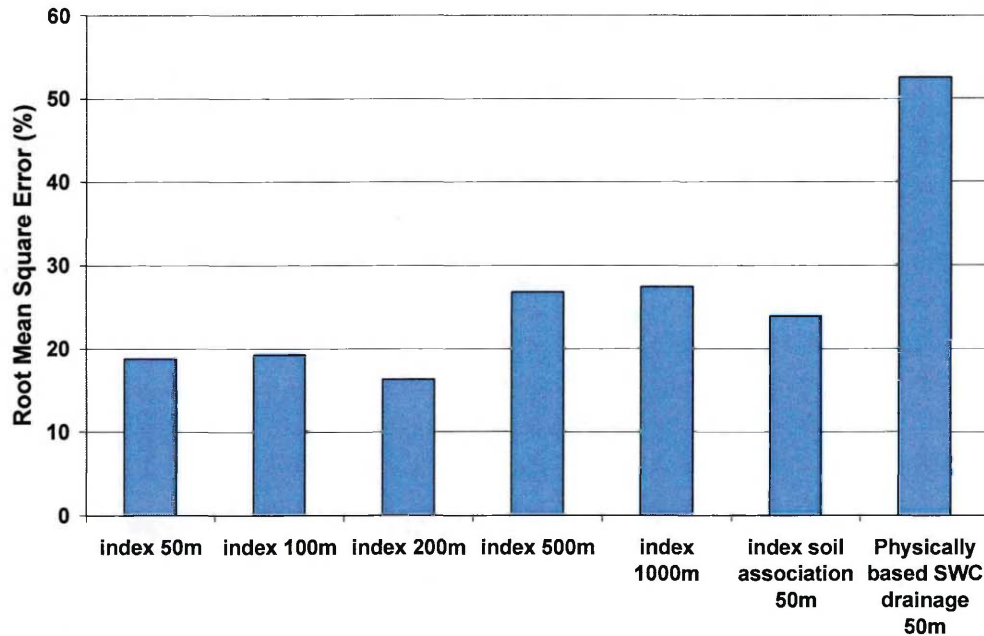


Figure 8-6 Root Mean Square Error (RMSE) between yield modelled at 50m using 1:25,000 scale soil series data using the Physically based STAMINA model and the FC drainage function and yield modelled at 50 m, 100 m, 200 m, 500 m and 1km grid sizes using 1:25,000 scale soil series data using the Index Based approach and at 50 m grid size using 1:250,000 scale soil association data and the Index based approach and yield modelled at 50m using 1:25,000 scale soil series data using the Physically based STAMINA model and the SWC drainage function

8.4 Major results

The key findings from this chapter are:

- The grid size should not exceed 100 m in order to sufficiently display the spatial distribution in yield;
- Decreasing the resolution of scale of the soil map, so the area is represented using larger taxonomic units, has a larger impact on the resulting yield estimate than increasing the grid size of the DTM.

9 Conclusions

9.1 Introduction

The aim of this thesis was to model soil moisture in the landscape in time and space and incorporate these results into a method for applying the STAMINA crop model at a regional level. The study has produced a significant new soil moisture data set along with further insight into the interaction of soils and terrain for predicting soil moisture. It has also shown that an index approach may be a potential method for applying the STAMINA model at a regional level. Furthermore it offers a sensitivity analysis that provides an understanding of the major drivers in the STAMINA model.

The **specific objectives** in this thesis were addressed and the key findings are outlined below.

Objective 1: To investigate data sets and methods which can be used to model the controls on soil moisture in the landscape and to determine the scales at which they are available for use (*Addressed in Chapters 2 and 4*)

The potential for soils and terrain data for being a major factor in explaining soil moisture patterns was identified from the literature. The data sets which were compiled for this study were varying scales of soil maps and profile descriptions in combination with Ordnance Survey Land-Form PROFILETM Elevation data

Objective 2: To collect field data in order to model the spatial and temporal variability of soil moisture within the STAMINA field sites (*Addressed in Chapter 3*)

A comprehensive new data set was compiled as part of this study. This included 2 growing seasons worth of soil moisture profile data at 6 depths from 100 mm to 1 m at 38 points in 2 fields using Delta-T PR1 profile probes and access tubes, 8 surface soil moisture surveys of over 100 points each in 3 different fields with differing soil characteristics using a Delta-T ML2 soil moisture probe. Weather data was also collected in the experimental catchments.

Objective 3: (*Addressed in Chapter 4 and 5*) To collect field data in order to develop regression models to explain the spatial and temporal variability of soil moisture within the STAMINA field sites

Regression Models were developed and suggested that the major driver of soil moisture at a field scale was soil properties, in particular the localised drainage characteristics of the soil profile. The results indicate that spatial organisation of soil moisture increases from the period immediately following a rainstorm event. In addition this research shows that in the absence of detailed soils data, terrain data provides significant additional information about the distribution of soil moisture

It appears that soil textural data at the measurement depth explains less of the soil moisture variation than a combination of depth and soil series, suggesting that the interaction of the soil layers in the profile is more important than the water holding capacity at the measurement point. The results also showed that the patterns of soil moisture in the landscape become increasingly stable with depth.

Objective 4: To develop a method of applying the STAMINA model at a regional level based on the analysis of soil moisture in the landscape (*Addressed in Chapter 6*)

A method for applying the STAMINA model at a regional level was developed based on an index based approach to distributing temperature, solar radiation and rainfall in the landscape. It is suggested that this is appropriate as available water is a major driver of crop growth and the soil moisture results show that up to 80% of the variation in soil moisture is determined by a combination of soils and terrain. Soils data is an integral part of the model with the vertical drainage being modelled based on water retention characteristics in the soil profile.

Objective 5: To apply sensitivity analysis to the regionalised modelling approach and to assess the appropriateness of the model in the light of the data available at a regional level (*Addressed in Chapters 7 and 8*)

The major driver of the STAMINA model is soils data. The results of the sensitivity analysis into the drainage function suggest that the key factor driving yield results is the ability of a soil to recharge over the winter months and how quickly it then dries

out over the summer based on its water holding capacity. It is therefore of utmost importance that the correct drainage function and associated parameters. The study shows that when comparing the drainage to measured data the function based on saturated water content predicts the pattern best. It does however show that increased water stress in clay soils which have higher available water than sandy soils. The results of this study show that there is a much greater effect of changing the drainage function in the STAMINA model than changing the form of the micro-meteorological part of the model from physically based approach to an index based approach.

The importance of soils and terrain has been shown to be a major driver in yield predictions in many studies. In particular Iqbal et al, (2005) showed that soil properties were more important in predicting yield variations than terrain variation. This is consistent with the findings with the outputs from the STAMINA model.

Objective 6: To assess the methods developed in the light of available data and the potential use for the modelling of risk in agriculture (*Addressed in Chapter 8*)

Grid size of the DTM has been shown to be important in the picking out of patterns in the landscape relating to low yield. A grid size of 100 m is thought to be sufficient for the study area. The scale of the soil map is a more critical issue as soils data are only available in the UK at 1:250,000 scale at a national level. This study has shown that decreasing the detail in the soil map from 1:25,000 to 1:250,000 changes both the pattern of modelled yield data and increases the RMSE to the same value as increasing the grid size to 500 m. There are still many issues to be resolved in the STAMINA model and it is suggested that if detailed soils data and digital terrain information is available this may be sufficient to highlight areas of low yield potential.

9.2 Soil moisture variation

The results from both surface soil moisture measurements and profile measurements suggest that soil properties are the major driver of soil moisture. Analysis of the profile measurement shows that soil series (mapped at 1:10,000 scale) are a better predictor of soil moisture than the soil texture at the measurement point. This is thought to be because the measurement point is not independent in space and there is

an interaction with the soil surrounding it which is better predicted by the detailed (1:10,000 scale) soil units. This suggests that at a field scale, processes occurring in small units within the field are more significant in determining soil moisture than the specific soil texture at a point.

Analysis of the surface measurements show that soil series mapped at 1:10,000 scale are a better predictor of soil moisture than soil series mapped at 1:25,000 scale. It appears that if the soil units become too generalised they are no-longer representing the factors which control soil moisture in the landscape.

The results of this study suggest that more generalised soil data is enhanced by the addition of terrain into the model describing soil moisture. This could be due to the interaction of soils and terrain in the landscape. In this study area a 1:10,000 scale soil map highlights most of the variation in soil moisture that is due to soil and terrain. A 1:25,000 scale soil map, however, does not provide all the information of the variation of soils in terrain. A key finding of this study has also been that the effects of soil and terrain on surface soil moisture are much larger in areas with both increased terrain variations and increased variation in the drainage characteristics which result from differing underlying geology.

9.3 The STAMINA model

This study proposes a method to apply the results of the STAMINA model at a regional level. The method simplifies complex physically based approach to distribute wind speed and direction, global and net radiation, soil latent and sensible heat fluxes and air temperature in the landscape to one using indices to distribute rainfall, temperature and global radiation in order to decrease the run time.

The index approach attempts to model the three dimensional movement of water in hill slopes. In this respect it is more complex than the physically based model, which does not take into account the lateral flow of water in the landscape. It is based on the premise that terrain and soils are the major drivers of soil moisture in the landscape, with terrain influencing the flow of water between cells and therefore, combined with rainfall the water available at each cell for crop growth. This assumption is seen to hold, particularly in areas where terrain and soil show major variations across a

landscape. The available water arriving at a model cell is distributed vertically in the soil profile by the soil hydrology module. This vertical redistribution of water at each cell is driven by soil properties. The solar radiation distribution within the landscape is driven by an index developed from a simplified physically based approach using long term average parameters measured in the vicinity of the study area.

The modelled yield from the index based approach shows significant correlation with the physically based approach for distributing meteorological variables with respect to terrain. It is proposed that the index based approach is an acceptable way to model terrain variations in agricultural indicators due to its ability to highlight, spatially, areas of different yield response which correspond to the areas predicted by the calibrated physically based approach. This is thought to be due to yield predictions in both versions of the model being driven by soil property data.

Sensitivity analysis shows that some limitations should be imposed on the implementation of the index based approach. Firstly the maximum grid size for a region should be determined. In the study area used in this study it is shown that a grid size of 100 m should not be exceeded.

The results of this study suggest that it is not possible to develop a generic regression equation between yield in the two approaches, in a specific region, and in some years no relationship appears to exist. This is the case in extremely dry years, for example 2003, where the models fail to produce a reliable crop yield. Furthermore individual soil series appear to respond differently in the two versions of the model. The use of the regression approach in this context is not recommended. Two alternative methods are proposed here:

- One approach would be to run the index based model at a regional level and then to run the physically based STAMINA model for specific areas of interest;
- The alternative approach that would be to make an assessment of the risk associated with agriculture based on soils data alone. This is considered an appropriate simplification as soil series predicts over 80% of the variation in yield in both the physically based and index based model approaches

Both these regional assessments, however, require sufficiently detailed soils data. Sensitivity analysis in this study has shown that changing the scale of soils data from 1:25,000 to 1:250,000 changes the predictions in the yield by the same amount as changing the DTM grid size for running the model from 50 m to 500 m (where sensitivity analysis has shown a 100 m grid is the appropriate grid size for this study area). It also changes the spatial pattern of yield predictions. There is therefore a problem in making regional assessments of any kind using 1:250,000 soils data.

In England and Wales, where 1:25,000 soils data are available an initial risk assessment of:

- Crop suitability in a given landscape;
- Changes in management practices which may be required as a result of changing climate;
- Water stress for a specific crop.

could be made for each soil series using the soil bulletins produced by soil surveyors. If this data could be linked to the soil assessments that farmers are required to undertake for the entry level stewardship schemes (DEFRA, 2005) they could be advised on how to change their management practices in response to changing water availability. This could help to mitigate the adverse impacts of potential changes in climate.

Preliminary investigations carried out as part of this study have shown that there are potential problems with some of the functions in the STAMINA model. The model appears, for example, to be much more sensitive to a change in the drainage function than to change in the form of the micro-meteorological sub-model.

In order to fully understand these observations a systematic study is required. Firstly there needs to be a determination of the soils and their properties that respond differently depending on the drainage function used. Secondly there needs to be a comparison of the model results for both drainage functions using:

- One soil series over an entire region with distributed meteorological parameters;
- Non distributed meteorological parameters with spatially variable soils.

It is recommended that study should be validated with comprehensive yield mapping in hilly terrain in a variety of soils.

However, topography may become a more important driver in the model as the terrain becomes more extreme. It is suggested that the spatial distribution of soils input into the model should still be carefully considered, as in areas of extreme terrain soil properties are also driven to a larger extent by terrain.

9.4 Conclusion and recommendations

Drainage characteristics and soil properties have been shown to be a driver of yield in the landscape in many previous studies. This study has shown that they are both key drivers of soil moisture distribution at a hill slope scale and also key drivers in predictions of yield in both versions of the STAMINA model.

Firstly the predicted drainage through the soil and the soil moisture time series are dependant on soil textural characteristics and therefore the water holding capacity of the soils. This is shown in the results from the STAMINA model simulations for known soil profile characteristics. These characteristics are also seen to influence the modelled yield with sandy areas showing lower yield predictions than soils with higher clay content. In addition to this both the soil moisture time series and yield are influenced by the model formulation, with two drainage functions giving contrasting responses in the same series. It would appear from these findings that the drainage function and therefore the ability of the soil moisture to recharge over the winter months has a larger impact on the yield results than the actual soil properties. Further investigations are required in order to quantify this observation.

In conclusion this study has highlighted the importance of understanding soil variations in the landscape and how they affect both modelled crop yield and soil water dynamics in a hill slope. The interactions between soils, terrain and soil moisture, at different scales, fit with the emerging field of “Hydropedology” (Lin *et al.*, 2006b). They also suggest that the full soil profile and underlying geology needs to be considered when considering water movement in a hill slope. Further investigations of the surface and profile soil moisture measurements in Stone Hill and Church Meadow could be used to build up a conceptual model of water in this small

agricultural catchment. This would be further enhanced if stream flow data were also used. Terrain is also an important influence in these process as it has been shown, in this study, that when detailed soils data is not available it can be used as a enhance less detailed soils data. Further investigations in these areas will aid the understanding of the processes, which occur and the scales at which they take place.

Models and indices, which make use of simplified processes and are designed to give the integrated output for a catchment, may however be sufficient to represent the processes occurring at a catchment or basin scale. In agricultural modelling soil appears to be a major driver of yield predictions. It is suggested that changes in management practices, required by climate change, could also be linked to soils and drainage characteristics. Advances in mapping of soils in the landscape are key to furthering our understanding of hill slope hydrology - its impacts on natural processes and its influence on land management practices.

10 References

- Alley, W.M., Healy, R.W., Labaugh, J.W. & Reilly, T.E. (2002) Hydrology - Flow and Storage in Groundwater Systems. *Science*, 296 (5575), 1985-1990.
- Aryal, S.K., Mein, R.G. & O'loughlin, E.M. (2003) The Concept of Effective Length in Hillslopes: Assessing the Influence of Climate and Topography on the Contributing Areas of Catchments. *Hydrological Processes*, 17 (1), 131-151.
- Bardossy, A. & Lehmann, W. (1998) Spatial Distribution of Soil Moisture in a Small Catchment. Part 1: Geostatistical Analysis . *Journal of Hydrology*, 206 (1-2), 1-15.
- Barling, R.D., Moore, I.D. and Grayson, R.B. (1994) The quasi-dynamic wetness index for characterizing the spatial distribution of zones of surface saturation and soil water content. *Water Resources Research*, 30, 1029-1044.
- Brady, N.C. & Weil, R.R. (1998) *The nature and properties of soils*. 12th ed. Harlow: Prentice Hall.
- Behrens, T., Gerber, R. and Scholten, T. Digital mapping of peri-glacial slope deposits using ground penetrating radar surveys on representative study sites. *Unpublished*,
- Beven, K. (1997) TOPMODEL: A critique. *Hydrological Processes*, 11, 1069-1085.
- Beven, K. and Wood E.F (1983) Catchment geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology*, 65, 139-158.
- Beven, K.J. and Kirkby, M.J. (1979) A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24, 43-68.
- Bierkens, M.F.P., Finke, P.A. & De Willigen, P. (2000) *Developments in plant and soil science: Upscaling and downscaling methods for environmental research*. Dordrecht: Kluwer Academic Publisher.

- Bonner, J, Conrad, D, Ringler, A, SAGA, System for Automated Geoscientific Analyses, Abteilung für Physische Geographie Geographisches Institut, Göttingen,
<http://www.saga-gis.uni-goettingen.de/html/index.php>
- Borga, M., Fontana G.D and Cazorzi F (2002) Analysis of topographic and climatic control on rainfall-triggered shallow landsliding using quasi-dynamic wetness index. *Journal of Hydrology*, 268, 56-71.
- Brasington, J. and Richards, K. (1998) Interactions between model predictions, parameters and DTM scales for TOPMODEL. *GeoComputation*, 24, 299-314.
- Breshears, D.D. & Barnes, F.J. (1999) Interrelationships Between Plant Functional Types and Soil Moisture Heterogeneity for Semiarid Landscapes Within the Grassland/Forest Continuum: a Unified Conceptual Model. *Landscape Ecology*, 14 (5), 465-478.
- Brown, C.D., Hollis, J.M., Bettison, R.J., Beulke, S., & Fryer, C.J. (1997) *Pesticide mobility: Lysimeter study to validate the relative leaching potential of UK soils*. PL0510, Soil Survey and Land Research Centre, Cranfield University.
- Brown, C.D., Hollis, J.M., Bettison, R.J. and Walker, A. (2000) Leaching of pesticides and a bromide tracer through lysimeters in five contrasting soils. *Pest Management Science*, 56, 83-93.
- Burrough, P.A., van Gaans, P.F.M. and MacMillan, R.A. (2000) High resolution landform classification using fuzzy *k*-means. *Fuzzy Sets and Systems*, 113, 37-52.
- Burt, T.P. & Butcher, D.P. (1985) Topographic Controls of Soil-Moisture Distributions. *Journal of Soil Science*, 36 (3), 469-486.
- Burton, R (2003) 1:10,000 scale soil maps of Stone Hill and Church Meadow

- Buttafuoco, G., Castrignano, A., Busoni, E. & Dimase, A.C. (2005) Studying the Spatial Structure Evolution of Soil Water Content Using Multivariate Geostatistics. *Journal of Hydrology*, 311 (1-4), 202-218.
- Buttle, J.M., Dillon, P.J. and Eerkes, G.R. (2004) Hydrological coupling of slopes, riparian zones and streams: an example from the Canadian Shield. *Journal of Hydrology*, 287, 161-177.
- Canton, Y., Sole-Benet, A. and Domingo, F. (2004) Temporal and spatial patterns in semiarid badlands of SE Spain. *Journal of Hydrology*, 285, 199-214.
- Cosh, M.H., Jackson, T.J., Starks, P. & Heathman, G. (2006) Temporal Stability of Surface Soil Moisture in the Little Washita River Watershed and Its Applications in Satellite Soil Moisture Product Validation. *Journal of Hydrology*, 323 (1-4), 168-177.
- Crave, A. and Gascuel-odoux, C. (1997) The Influence of Topography on Time and Space Distribution of Soil Surface Water Content. *Hydrological Processes*, 11 (2), 203-210.
- De Bruin, S. and Stein, A. (1998) Soil landscape modelling using fuzzy *c*-means clustering of attribute data derived from a Digital Elevation Model (DEM). *Geoderma*, 83, 17-33.
- De Vries, W., Kros, J., van der Salm, C., Groenenberg J.E and Reinds G.J (1998) The use of upscaling procedures in the application of soil acidification models at different spatial scales. *Nutrient Cycling in Agroecosystems*, 50, 223-236.
- DEFRA (2005) *Producing a soil management plan for environmental stewardship*. Department for Environment, Food and Rural Affairs.
<http://www.defra.gov.uk/erdp/schemes/es/soilmanagementplan.htm>
- Delta-T Devices Ltd (1999) *User manual for the Theta Probe soil moisture sensor: Type ML2x*.
<http://www.delta-t.co.uk/support-article.html?article=faq2005100703502>
- Delta-T Devices Ltd (2001) *User manual for the profile probe: type PR1*.

<http://www.delta-t.co.uk/support-article.html?article=faq2005092821623>

Delta-T Devices Ltd (2004) *Weather stations product information*.

<http://www.delta-t.co.uk/support-article.html?article=faq2005092822299>

Dingman, S.L. (2002) *Physical Hydrology*. Upper Saddle River, New Jersey: Prentice Hall.

Dubayah, R. & Rich, P.M. (1995) Topographic solar radiation models for GIS. *International Journal of Geographic Information Systems*, 9 (4), 405-419.

Duguay, C.R., (1993) Radiation modelling in mountainous terrain: Review and status. *Mountain Research and development*, 13, 339-357

European Comission (2005) *Europe in figures: Eurostat yearbook, 2005*. EUROSTAT. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-CD-05-001-2/EN/KS-CD-05-001-2-EN.PDF

European Commision (2003) *Monitoring agiculture with remote sensing bulletin*. Vol.11 No.5, European Commision, Joint Research Centre
<http://www.mars.jrc.it/stats/bulletin>

Fernandez-Galvez, J., Simmonds, L.P. & Barahona, E. (2006) Estimating Detailed Soil Water Profile Records From Point Measurements. *European Journal of Soil Science*, 57 (5), 708-718.

Florinsky, I.V., Eilers, R.G., Manning, G.R. and Fuller, L.G. (2002) Prediction of soil properties by digital terrain modelling. *Environmental Modeling and Software*, 17, 295-311.

Florinsky, I.V. and Kuryakova, G.A. (2000) Determination of grid size for digital terrain modelling ladscape investigations - exemplified by soil moisture distribution at a micro-scale. *International Journal of Geographic Information Science*, 14, 815-832.

Frankenberger, J.R., Brooks, E.S., Walter, M.T., Walter, M.F. and Steenhuis, T.S. (1999) A GIS-based variable source area hydrology model. *Hydrological Processes*, 13, 805-822.

- Fu, B., Wang, J., Chen, L. and Qui, Y. (2003) The effects of land use on soil moisture variation in Danangou catchment of the Loess Plateau, China. *Catena*, 54, 197-213.
- Gallant, J.C. and Wilson, P. (1996) TAPES-G: A grid-based terrain analysis program for the environmental sciences. *Computers and Geosciences*, 22, 713-722.
- Garbrecht, J and Martz, L (1992), TOPAZ, Topographic Parameterization Software, GrazingLands Research Laboratory,
<http://www.grl.ars.usda.gov/topaz/TOPAZ1.HTM>
- Gaskin, G.J. and Miller, J.D. (1996) Measurement of soil water content using a simplified impedance technique. *Journal of Agricultural Engineering research*, 63, 153-160.
- Gomez-Plaza, A., Martinez-Mena, M., Albaladejo, J. and Catillo, V.M. (2001) Factors regulating spatial distribution of soil water content in small semiarid catchments. *Journal of Hydrology*, 253, 211-226.
- Grayson, R.B. & Western, A.W. (1998) Towards Areal Estimation of Soil Water Content from Point Measurements: Time and Space Stability of Mean Response. *Journal of Hydrology*, 207 (1-2), 68-82.
- GSWP (2004) *Global Soil Wetness Project Report*. <http://grads.iges.org/gswp/report>
- Hawley, M.E., Jackson, T.J. and McCuen, R.H. (1983) Surface soil moisture variation on small agricultural watersheds. *Journal of Hydrology*, 62, 179-200.
- Hebrard, O., Voltz, M., Andrieux, P. & Moussa, R. (2006) Spatio-Temporal Distribution of Soil Surface Moisture in a Heterogeneously Farmed Mediterranean Catchment. *Journal of Hydrology*, 329 (1-2), 110-121.
- Hengl, T. (2006) Finding the Right Pixel Size. *Computers & Geosciences*, 32 (9), 1283-1298.
- Hodgson, J.M. (1976) *Soil Survey field handbook: Describing and sampling soil profiles*. Harpenden: Adlard and Son Ltd.

- Horton, R.E. (1945) Erosional development of streams and their drainage basins; Hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin*, 56, 275-370.
- Howard, J.A. and Mitchell, C.W. (1980) Phyto-Geomorphic classification of the landscape. *Geoforum*, 11, 85-106.
- Hulme, M., Turnpenny, J., & Jenkins, G. (2002) *Climate change scenarios for the United Kingdom: The UKCIP02 briefing report*. Tyndal climate change research, School of environmental sciences, University of East Anglia.
- Hutchinson, M.F. (1989) A new procedure for gridding elevation and stream line data with the automatic removal of spurious pits. *Journal of Hydrology*, 106, 211-232.
- Iqbal, J., Read, J.J., Thomasson, A.J. and Jenkins, J.N. (2005) Relationships between soil-landscape and dryland cotton lint yield. *Soil Science Society America Journal*, 69, 872-882.
- Irmak, A., Jones, J.W., Batchelor, W.D. and Paz, J.O. (2001) Estimating spatially variable soil properties for application of crop models in precision farming. *Transactions of the ASAE*, 44, 1343-1353.
- Irvin, B.J., Ventura, S.J. and Slater, B.K. (1997) Fuzzy and isodata classification of landform elements from digital terrain data in Pleasant Valley, Wisconsin. *Geoderma*, 77, 137-154.
- Jacobs, J.M., Mohanty, B.P., Hsu, E.C. & Miller, D. (2004) Smex02: Field Scale Variability, Time Stability and Similarity of Soil Moisture. *Remote Sensing of Environment*, 92 (4), 436-446.
- Jaynes D.B, Kaspar, T.C., Colvin, T.S. and James, D.E. (2003) Cluster analysis of spatiotemporal corn yield patterns in Iowa Field. *Agronomy Journal*, 95, 574-586.

- Kang, S., Kim, S., Oh, S. and Lee, D. (2000) Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. *Forest Ecology and Management*, 136, 173-184.
- Kaspar, T.C., Pulido, D.J., Fenton, T.E., Colvin, T.S., Karlen, D.L., Jaynes D.B and Meek D.W (2004) Relationship of corn and soybean yield to soil and terrain properties. *Agronomy Journal*, 96, 700-709.
- Kienzle, S. (2004) The effect of DEM raster resolution on first order, second order and compound terrain derivatives. *Transactions in GIS*, 8, 83-111.
- Killham, K. (1994) *Soil Ecology*. Cambridge: Cambridge university press.
- King, D., Fox, D.M., Daroussin, J., Le Bissonais, Y. and Danneels, V. (1998) Upscaling a simple erosion model from small areas to a large region. *Nutrient Cycling in Agroecosystems*, 50, 143-149.
- Kravchenko, A.N. and Bullock, D.G. (2002) Spatial variability of soybean quality data as a function of field topography: I. Spatial data analysis. *Crop Science*, 42, 804-815.
- Kravchenko, A.N., Robertson, G.P., Thelen, K.D. and Harwood, R.R. (2005) Management, topographical and weather effects on spatial variability of crop grain yields. *Agronomy Journal*, 97 (2) 514-523.
- Kumar, L., Skidmore, A.K. and Knowles, E. (1997) Modelling topographic variation in solar radiation in a GIS environment. *Geographic Information Science*, 11 (5), 475-497
- Kumar, P., Verdin, K.L. & Greenlee, S.K. (2000) Basin Level Statistical Properties of Topographic Index for North America. *Advances in Water Resources*, 23 (6), 571-578.
- Lagacherie, P., Cazemier, D.R., van Gaans, P.F.M. and Burrough, P.A. (1997) Fuzzy *k*-means clustering of fields in an elementary catchment and extrapolation to a larger area. *Geoderma*, 77, 197-216.

- Lagacherie, P., Robbez-Masson, J.M., Nguen-The, N. and Bartčs, J.P. (2001) Mapping reference area representivity using mathematical soilscape distance. *Geoderma*, 101, 105-118.
- Lal, R. & Shukla, M.K. (2004) *Principles of soil physics*. New York: Marcel Dekker, Inc.
- Lamb, R., Beven, K. & Myrabo, S. (1997) Discharge and Water Table Predictions Using a Generalized Topmodel Formulation. *Hydrological Processes*, 11 (9), 1145-1167.
- Lark, R.M. and Stafford, J.V. (1998) Information on within field variability from sequences of yield maps: multivariate classification as a first step of interpretation. *Nutrient Cycling in Agroecosystems*, 50, 277-281.
- Lauzon, N., Anctil, F. & Petrinovic, J. (2004) Characterization of Soil Moisture Conditions at Temporal Scales From a Few Days to Annual. *Hydrological Processes*, 18 (17), 3235-3254.
- Leenhardt, D., Voltz, M., Bornard, M. and Webster, R. (1994) Evaluating soil maps for predicting soil properties. *European Journal of Soil Science*, 45, 293-301.
- Lin, H. (2006) Temporal Stability of Soil Moisture Spatial Pattern and Subsurface Preferential Flow Pathways in the Shale Hills Catchment. *Vadose Zone Journal*, 5 (1), 317-340.
- Lin, H.S., Kogelmann, W., Walker, C. & Bruns, M.A. (2006a) Soil Moisture Patterns in a Forested Catchment: a Hydropedological Perspective. *Geoderma*, 131 (3-4), 345-368.
- Lin, H., Bouma, J., Pachepsky, Y., Western, A., Thompson, J., Van Genuchten, R., Vogel, H.J. & Lilly, A. (2006b) Hydropedology: Synergistic Integration of Pedology and Hydrology. *Water Resources Research*, 42 (5)
- Lindsay, J (2003), TAS, Terrain Analysis Software,
<http://www.sed.manchester.ac.uk/geography/research/tas/>

- Liu, M. and Samal, A. (2002) A fuzzy clustering approach to delineate agroecozones. *Ecological Modelling*, 149, 215-228.
- Ma, K.M., Fu, B.J., Liu, S.L., Guan, W.B., Lü, Y.H. and Anand, M. (2004) Multiple-scale soil moisture distribution and its implications for ecosystem restoration in an arid river valley, China. *Land Degredation and Development*, 15, 75-85.
- MacMillan, R.A., McNabb, D.H., & Jones R.K (2000a) Automated landform classification using DEMs: a conceptual framework for multi-level, hierachy of hydrological and geomorphically oriented mapping units, *4th International conference on integrating GIS and environmental modelling (GIS/EM4) Problems, prospects and research needs*, Banff, Alberta, Canada,
- MacMillan, R.A., Pettapiece, W.W., Nolan, S.C. and Goddard, T.W. (2000b) A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic. *Fuzzy Sets and Systems*, 113, 81-109.
- Maidment D.R (2002) *Arc Hrdro: GIS for water resources*. Redlends, CA: ESRI.
- Martinez-Fernandez, J. & Ceballos, A. (2003) Temporal Stability of Soil Moisture in a Large-Field Experiment in Spain. *Soil Science Society of America Journal*, 67 (6), 1647-1656.
- Mayr, T.M., Jarvis, N.J., & Simota, C. (1999) Pedotransfer functions for soil water retention characteristics. In: *Proceedings of the international workshop: Characterisation and measurement of the hydraulic properties of porous media*, Riverside,
- McBratney, A.B. (1998) Some considerations on methods for spatially aggregating and disaggregating soil information. *Nutrient Cycling in Agroecosystems*, 50, 51-62.
- McKenny, D.W., MacKey, B.G. and Zavitz, B.L. (1999) Calibration and sensitivity analysis of a spatially distributed solar radiation model. *International Journal of Geographic Information Science*, 13, 49-65.

- McKenzie, N.J and Ryan, P.J (1999) Spatial prediction of soil properties using environmental correlation, *Geoderma* 89: 67-94
- Mohannty, B.P. and Skaggs, T.H. (2001) Spatio-temporal evolution and time scale characteristics of soil moisture within remote sensing footprints with varying soil, slope and vegetation. *Advances in Water Resources*, 24, 1051-1067.
- Moore, I.D., Gessler, P.E., Nielsen, G.A. & Peterson, G.A. (1993) Soil Attribute Prediction Using Terrain Analysis. *Soil Science Society of America Journal*, 57 (2), 443-452.
- Moore, I.D., Grayson, R.B. and Ladson, A.R. (1991) Digital terrain modelling: A review of hydrological, geomorphological and biological applications. *Hydrological Processes*, 5, 3-30.
- Moore, I.D., Norton, T.W. and Williams, J.E. (1993) Modelling environmental heterogeneity in forested landscapes. *Journal of Hydrology*, 150, 717-747.
- Naden, P.S., Blyth, E.M., Broadhurst, P., Watts, C.D. & Wright, I.R. (2000) Modelling the Spatial Variation in Soil Moisture at the Landscape Scale: an Application to Five Areas of Ecological Interest in the UK. *Hydrological Processes*, 14 (4), 785-809.
- Nandakumar, N., Lane, P.N.J., Vertessy, R.A. & O'Loughlin, E.M. (1994) Prediction of soil moisture variability using wetness indices, *Water Down Under 94: Proceedings of the Australian Institution of Engineers Hydrology and Water Resources Symposium*, Adelaide, Vol. 3.
- National Union of Farmers (2005) *Agriculture and climate change*.
<http://www.nfuonline.com/documents/NFU%20climate%20change.pdf>
- Noilhan, J. and Planton, S. (1989) A simple parameterisation of land surface proccesses for meteorooogical models. *Monthly weather Review*, 117, 536-549.
- Nyberg, L. (1996) Spatial Variability of Soil Water Content in the Covered Catchment at Gardsjon, Sweden. *Hydrological Processes*, 10 (1), 89-103.

- O'Loughlin, E.M. (1981) Saturation regions in catchments and their relations to soil and topographic properties. *Journal of Hydrology*, 53, 229-246.
- O'Loughlin, E.M. (1986) Prediction of surface saturation zones in natural catchments by topographic analysis. *Water Resources Research*, 22, 794-804.
- Office of National Statistics (2005) *UK 2005, Th official year book of the United Kingdom of Great Britain and Northern Ireland*.
<http://www.statistics.gov.uk/downloads/theme-compendia/UK2005.pdf>
- Pachepsky Y.A, Timlin D.J and Rawls, W.J. (2001) Soil water retention as related to topographic variables. *Soil Science Society America Journal*, 65, 1787-1795.
- Parent, A.C., Anctil, F. & Parent, L.E. (2006) Characterization of Temporal Variability in Near-Surface Soil Moisture at Scales From 1 H to 2 Weeks. *Journal of Hydrology*, 325 (1-4), 56-66.
- Park, S.J. and van de Giesen, N. (2004) Soil-landscape delineation to define spatial sampling domains for hillslope hydrology. *Journal of Hydrology*, 295, 28-46.
- Pellenq, J., Kalma, J., Boulet, G., Saulnier, G.M., Wooldridge, S., Kerr, Y. & Chehbouni, A. (2003) A Disaggregation Scheme for Soil Moisture Based on Topography and Soil Depth. *Journal of Hydrology*, 276 (1-4), 112-127.
- Peters-Lidard, C.D., Pan, F., Hsu, A.Y. and O'Neil, P.E. (2001) ESTAR - and model-derived multiscaling characteristics of soil moisture during SGP'97 Washita '92 and Washita '94. *IEEE*, 1297-1299.
- Quinn, P., Beven, K. and Lamb, R. (1995) The $\ln(a/\tan B)$ Index: How to calculate it and how to use it in the TOPMODEL framework. *Hydrological Processes*, 9, 161-182.
- Quinn, T., Zhu, A.X. & Burt, J.E. (2005) Effects of Detailed Soil Spatial Information on Watershed Modelling Across Different Model Scales. *International Journal of Applied Earth Observation and Geoinformation*, 7 (4), 324-338.
- Reid, I. (1973) The influence of slope orientation upon the soil moisture regime, and its hydrogeomorphological significance. *Journal of Hydrology*, 19, 309-321.

- Richter, G.M., Acutis, M., Mayr, T., Rana, G., & Simota, C. Executive summary of the STAMINA final report. *unpublished*
- Richter, G.M., Acutis, M., Mayr, T., Rana, G., & Simota, C. (2003) How realistic is it to use model-based agro-ecological indicators for risk assessment: Proceedings of the Japan/OECD expert meeting. *In: OECD, Agriculture and land conservation developing indicators for policy analysis*, Kyoto, The Ministry of Agriculture, Forestry and Fisheries of Japan,
- Ridolfi, L., D'Odorico, P., Poporato, A. and Rodriguez-Itrube, I. (2003) Stochastic soil moisture dynamics along a hill slope. *Journal of Hydrology*, 272, 264-275.
- Robbez-Masson, J.M. (1994) Reconnaissance et délimitation de motifs d'organisation spatiale. Application à la cartographie des pédopaysages. PhD. Thesis. ENSA.M, Montpellier, 161 p. + ann
- Rodhe, A. and Seibert, J. (1999) Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators. *Agricultural and Forest Meteorology*, 98-99, 325-340.
- Romano, N. and Palladino, M. (2002) Prediction of soil water retention using soil physical data and terrain attributes. *Journal of Hydrology*, 265, 56-75.
- Romshoo, S.A. (2004) Geostatistical analysis of soil moisture measurements and remotely sensed data at different spatial scales. *Environmental Geology*, 45, 339-349.
- Rowell, D.L. (1994) *Soil science methods and application*. Harlow: Prentice Hall.
- Russell, G. and Wilson, G.W. (1994) *An Agro-pedo-climatalogical knowledge-base of wheat in Europe*. Brussels: European Comission.
- Salvucci, G.D., Saleem, J.A. and Kaufmann, R. (2002) Investigating soil moisture feedbacks on precipitation with tests of Granger causality. *Advances in Water Resources*, 25, 1305-1312.

- Schmidt, J., Hennrich, K. and Dikau, R. (2000) Scales and similarities in runoff processes with respect to geomorphology. *Hydrological Processes*, 14, 1963-1979.
- Seibert, J., Bishop, K.H. & Nyberg, L. (1997) A Test of Topmodel's Ability to Predict Spatially Distributed Groundwater Levels. *Hydrological Processes*, 11 (9), 1131-1144.
- Shreier, H. and Lavkulich L.M (1978) A numerical terrain classification scheme for off-road terrain trafficability assessments. *Geoforum*, 9, 225-234.
- Shukla, J. & Mintz, Y. (1982) Influence of Land-Surface Evapo-Transpiration on the Earths Climate. *Science*, 215 (4539), 1498-1501.
- Skinder, A.M. (2005) Quantifying landscape similarity comparing CAS and CLAPAS. MSc Thesis, Cranfield University
- Starks, P.J., Heathman, G.C., Jackson, T.J. & Cosh, M.H. (2006) Temporal Stability of Soil Moisture Profile. *Journal of Hydrology*, 324 (1-4), 400-411.
- Starr, G.C. (2005) Assessing Temporal Stability and Spatial Variability of Soil Water Patterns With Implications for Precision Water Management. *Agricultural Water Management*, 72 (3), 223-243.
- Stein, A., Riley, J. and Halberg, N. (2001) Issues of scale for environmental indicators. *Agriculture Ecosystems and Environment*, 87, 215-232.
- Svetlitchnyi, A.A., Plotnitskiy, S.V. and Stepovaya, O. (2003) Spatial distribution of soil moisture content and the modelling on the basis of topographic data. *Journal of Hydrology*, 277, 50-60.
- Taylor, C., Sannier, C., Delince & Gallego, F.J. (1997) *Regional crop inventories in europe assisted by remote sensing: 1988-1993: Synthesis report of the MARS project - Action 1*. Luxembourg: Joint Research Centre European Comission: Space Applications Institute, Agriculture.
- Thieken, A.H., Lücke, A., Diekkrüger, B. and Richter, O. (1999) Scaling input data by GIS for hydrological modelling. *Hydrological Processes*, 13, 611-638.

- Thompson J.A, Bell J.C and Butler C.A (2001) Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil landscape modelling. *Geoderma*, 100, 67-89.
- Thwaites, R.N. and Slater B.K (2000) Soil-landscape resource assessment for plantations - A conceptual framework towards an explicit multi-scale approach. *Forest Ecology and Management*, 138, 123-138.
- Vachaud, G, Desilans, A.P., Balabanis, P. & Vauclin, M. (1985) Temporal Stability of Spatially Measured Soil-Water Probability Density-Function. *Soil Science Society of America Journal*, 49 (4), 822-828.
- Vertessy, R., O'Loughlin, E.M., Beverly, C. & Butt, T. (1994) Australian experiences with the CSIRO TOPOG model in land and water resources management. *In: Anon., Proceedings of UNESCO International Symposium on Water Resources Planning in a Changing World*, Karlsruhe, Germany,
- Wang, H., Hall, C.A.S., Cornell, D. and Hall, M.H.P. (2002) Spatial dependence and the relationship of soil organic carbon and soil moisture in the Luquillo Experimental Forest, Puerto Rico. *Landscape Ecology*, 17, 671-684.
- Western A.W and Grayson R.B (1998) The Tarrawarra data set: Soil moisture patterns, soil characteristics, hydrological flux measurements. *Water Resources Research*, 34, 2765-2768.
- Western, A.W., Grayson, R.B. and Blöschl, G. (2002) Scaling of soil moisture: A hydrologic perspective. *Annual Reviews in Earth and Planetary Sciences*, 30, 149-180.
- Western A.W, Grayson R.B, Blöschl G, Willgoose G.R and McMahon T.A (1999) Observed spatial organisation of soil moisture and its relation to terrain indices. *Water Resources Research*, 35, 797-810.
- Western, A.W., Zhou, S., Grayson, R.B., McMahon, T.A., Blöschl, G. and Wilson, D.J. (2004) Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. *Journal of Hydrology*, 286, 113-134.

- White, R.E (1997) *Principles and practice of soil science – The soil as a natural resource* 3rd Ed. Blackwell Science, Oxford
- Wilson, D.J., Western, A.W. & Grayson, R.B. (2005) A Terrain and Data-Based Method for Generating the Spatial Distribution of Soil Moisture. *Advances in Water Resources*, 28 (1), 43-54.
- Wilson, J.P. & Gallant, J.C. (2000) *Terrain analysis principles and applications*. New York: Wiley.
- Wright, P.S. (1987) *Soils in Bedfordshire: Sheet TL14 (Biggleswade)*. Soil Survey Record No. 112 and 1:25,000 map. Harpenden:
- Zelege, T.B. and Si, B.C. (2004) Scaling properties and topographic indices and crop yield: Multifractal and joint multifractal approaches. *Agronomy Journal*, 96, 1082-1090.
- Zhang, W.H. & Montgomery, D.R. (1994) Digital Elevation Model Grid Size, Landscape Representation, and Hydrologic Simulations. *Water Resources Research*, 30 (4), 1019-1028.
- Zhu, A.X., Band, L., Vertessy, R. & Dutton, B. (1997) Derivation of Soil Properties Using a Soil Land Inference Model (SOLIM). *Soil Science Society of America Journal*, 61 (2), 523-533.

Appendix I

SRAD Input Parameters [Compiled by Mayr, 2006]

Climate

There are many ways to integrate rainfall, temperature and radiation data to provide indices of local climate. Simple indices of the water balance are amongst the most useful because they integrate biologically important effects of rainfall and evaporation. They give an indication of the intensity of leaching and provide a relative measure of potential biological productivity. They are, however, seldom used due to the limited extent of most study areas. A notable exception is the work by McKenzie and Ryan (1999), which used the Prescott Index to map a climatic water balance across their study area.

For this study, incoming SWRSS was calculated using the SRAD routine from TAPES-G (McKenney et al. 1999). Model input files were constructed according to McKenzie et al. (1999). For the Harold Hill sheet, meteorological data were available from Gatwick Airport, and data from Silsoe meteorological station.

Relevant input data for SRAD were calculated from daily meteorological data as follows:

Sunshine fraction:

The sunshine fraction, S , is the daily proportion of bright sunshine. Data describing this parameter were not directly available. Monthly average sunshine fraction for the study region was determined using:

$$S = n / N$$

where n is the actual number of hours of daily sunshine and N is proportional to the number of hours of daily sunshine (day length).

Cloudiness:

Cloudiness (β) is the monthly average fraction of actual radiation to potential radiation during cloudy periods (McKenney *et al.*, 1999):

$$\beta = (Q_s / Q_o - S) / (1 - S)$$

where Q_s is total irradiance (actual radiation) and Q_o is clear-sky total irradiance (potential radiance).

However, it was found that many days with low amounts of possible total sunshine ($n/N < 1$, cloudy days) often had higher total irradiance values than days with 100 % of possible sunshine. Therefore, maximum irradiance values were extracted for each day of the 26 or 27-year periods respectively and summed for each month to establish Q_o .

Atmospheric transmittance:

The clear-sky atmospheric transmittance at sea level (t) is the monthly fraction of solar radiation transmitted by the atmosphere (McKenney *et al.*, 1999):

$$t = (Q_o / Q_a) - 0.00008z$$

where Q_a is extraterrestrial irradiance, 8×10^{-5} is the typical lapse rate of atmospheric transmissivity in metres⁻¹, and z is elevation above sea level of the study area in metres.

Circumsolar coefficient:

The circumsolar coefficient of diffuse irradiance (D_c) is the monthly fraction of diffuse irradiance originating near the solar disc, within about five degrees of the direct solar beam (McKenney *et al.* 1999):

$$D_c = D \cdot Q_d / I_o \cdot 24$$

where D is the diffusive irradiance, Q_d is the direct irradiance, I_o is the insolation (or solar constant) and 24 is a constant.

Appendix II

Software available for calculating terrain indices, derivatives and characteristic lengths in hill slopes

Software and References	Outputs	Advantages	Disadvantages
TAPES-G (Wilson and Gallant, 1996) SRAD (Moore et al., 1993) DYNWET-G (Based on Barling et al., 1994)	Properties relevant to water distribution in the landscape. First and second derivatives and combinations defining upslope characteristics. Wetness Indices and Solar Radiation and Temperature	Linked software packages Outputs from TAPES-G can be used directly to calculate secondary attributes. Doesn't require river flow characteristics. Variety of options for including soils data in Wetness index. Variety of methods for calculating flow paths. Uses a grid based system.	LINUX Based. Processing of output files is very time consuming. Requirement for pre-processing to smooth the DTM for slope, Aspect curvature calculations
TAPES-C/ TOPOG (Vertessy et al., 1994)	Steady state parameters and dynamic soil moisture profiles etc.	Improved flow connectivity compared to a grid based system.	Difficult to construct the element network. No radiation indices calculated. Dynamic wetness calculations based on specific climatic conditions. Physically based model designed for dynamic hydrological modelling
LAND-MAPR (Macmillan et al., 2000)	Shape characteristics for landscapes defined by distances between streams and ridges.	Parameters can be used for characterisation of the landscape with respect to physical modelling	No indices calculated other than WI. No soils input.
TOPAZ (Garbrecht and Martz, 1992)	Sub catchment identification and channel parameters. Basic topographic derivatives	Allows a quality control on the DTM to be performed. Defines sub catchments.	Only uses the D8 method for defining water flow in the landscape. Does not calculate curvature parameters or link to terrain indices required for analysis Does not allow soils data input.

Software and References	Outputs	Advantages	Disadvantages
TOPOGRID (ArcInfo Based on ANUDEM, Hutchinson, 1989)	Smoothed DTM	Allows slope, aspect etc to be calculated without sinks in TAPES-G	N/A
ArchHydro (Maidment, 2002)	Channel networks and catchment boundaries.	Quick calculation and display of sub catchments within ArcGIS which can be used to extract parameters for similarity analysis	Only uses the D8 method for defining water flow in the landscape. Designed for hydrological modelling and not index development. No radiation analysis or option for soils data input
TAS (Lindsay, 2003)	Morphometric and stream characteristics. Classifications of landscapes.	A free terrain analysis software which allows the display of data.	Performs many of the functions of ArcGIS. Doesn't calculate radiation indices or allow soils input
TOPMODEL (Beven and Kirkby, 1979)	Produces hydrographs and topographic contributing area analysis	Prediction of soil moisture variations can be linked to stream flow predictions if data are available for both.	Hydrological model using Wetness Index and predicting stream flow and not a model that calculates multiple indices with a variety of input options.
SOLAR-FLUX (Dubayah and Rich, 1995)	Insolation with and without topographic shading. Duration of direct insolation. Compensation of transmissivity for elevation	Can be used directly in ArcINFO	Only a limited amount of solar outputs
SAGA development from DIGEM (Bonner et al., 2005)	Properties which define the shape of the landscape and the upslope area using various flow routing algorithms	A windows based system with immediate visual results. Two extra flow routing algorithms than TAPES-G	No Radiation Indices calculated. Soils data not included

Appendix III

Soil Survey Methodology [Compiled by Rodney Burton, 2003]

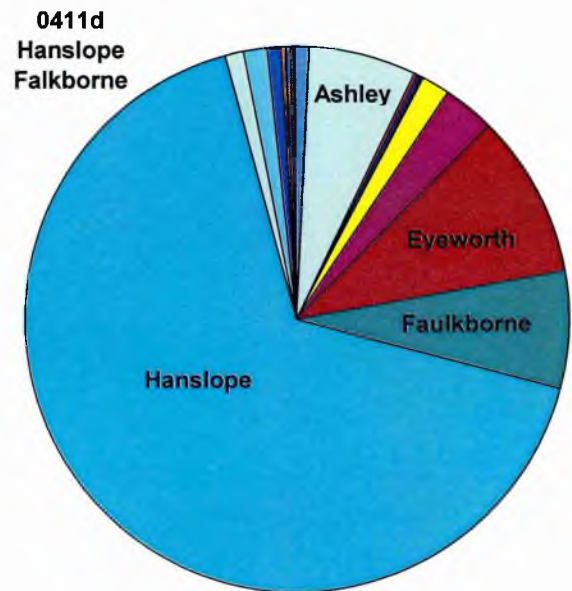
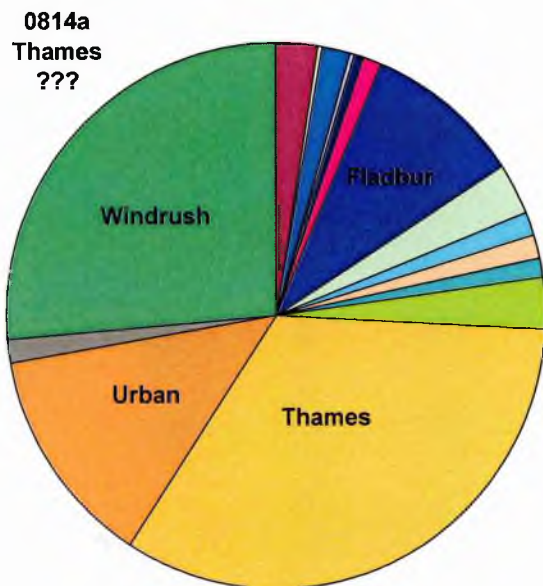
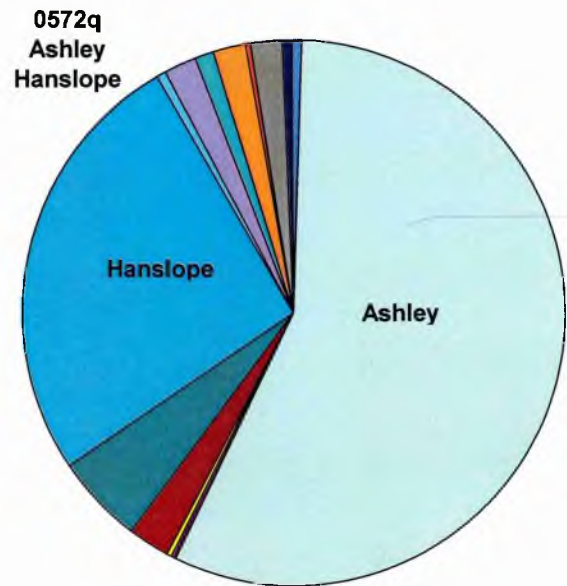
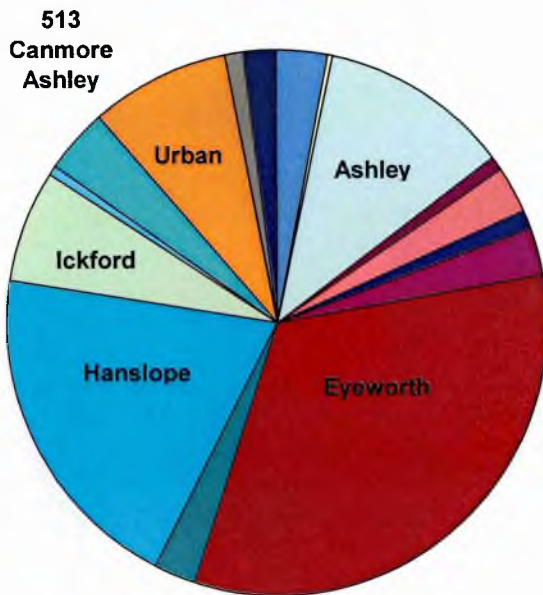
The survey work was carried out by an experienced soil surveyor from the National Soil Resources Institute of Cranfield University based at Silsoe in Bedfordshire.

The investigation at each site was made using a 4-cm wide Dutch (Edelman) auger. All soil layers to include both the topsoil and the subsoil, and the depths at which changes occurred, were studied to a depth of 1.1 metres. Properties such as texture, structure, colour and mottling, the presence of carbonate (free lime), drainage status and stones were recorded in accordance with the Soil Survey Field Handbook (Hodgson 1967). The data were entered onto a standard computer-compatible record card.

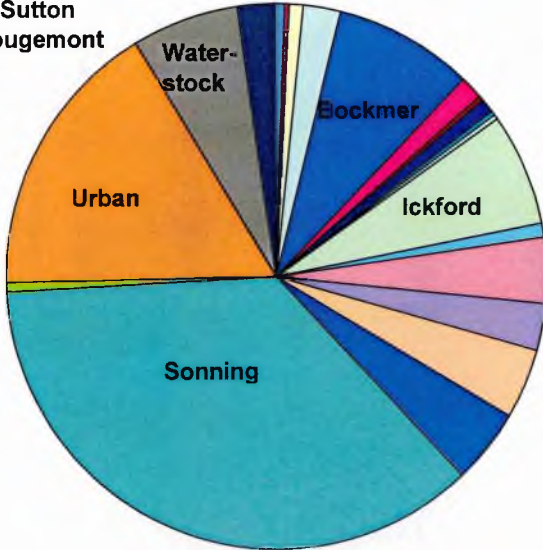
Initial investigation sites were adjacent to the tube installations (38 sites). Further investigation points were selected by the surveyor when in the field and not pre-determined. Their location and spacing were determined by the surveyor 'reading' the landscape-forming processes, as well as the pedological processes operating upon the soil parent materials; location also depended upon local soil variability.

Appendix IV

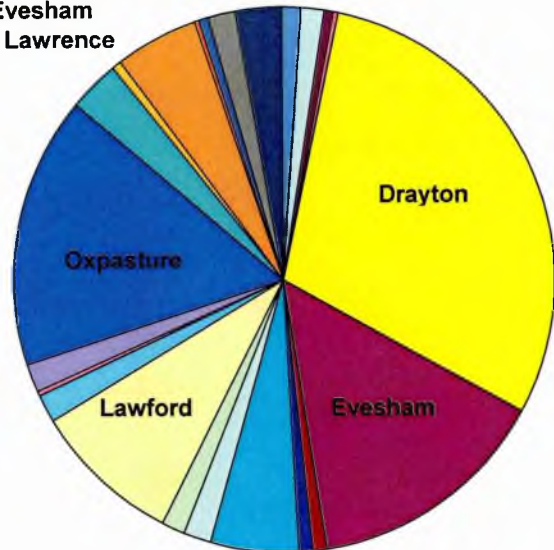
The following pie charts show the percentage of soil series mapped at 1:25,000 scale from the TL14 Biggleswade Map Sheet (Wright, 1987) in each of the soil association polygons at 1:250,000 scale. The headings for each chart show, in order, the soil association number and the first and second most dominant series in that association averaged at a national level.



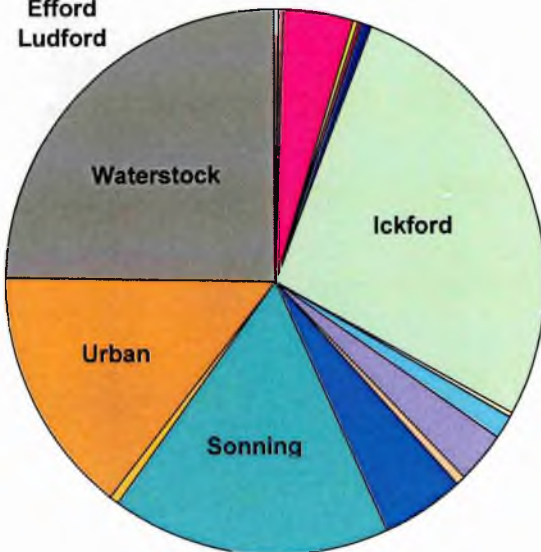
0571u
Sutton
Rougemont



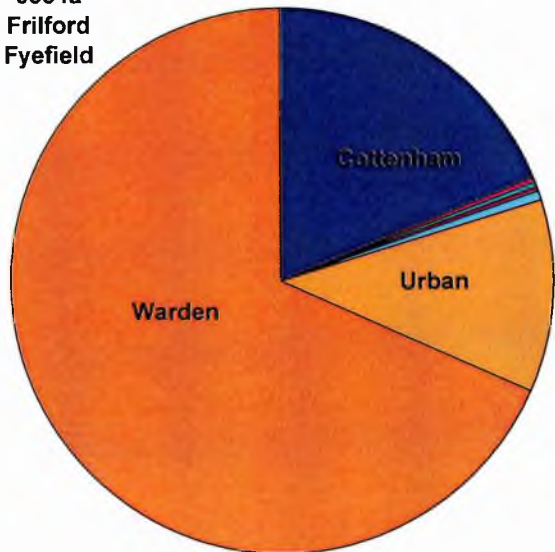
0411c
Evesham
St. Lawrence



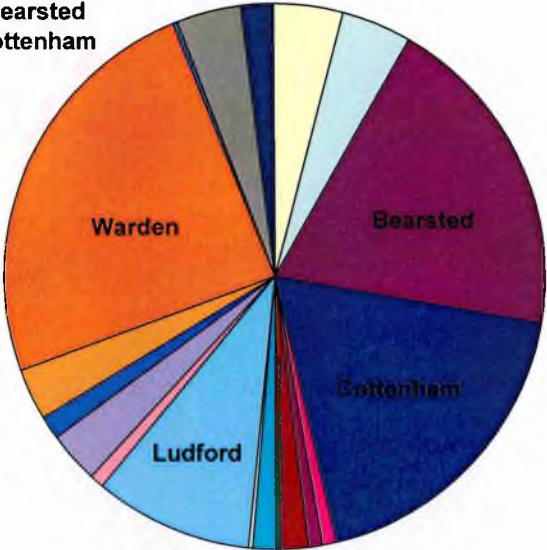
0571s
Efford
Ludford



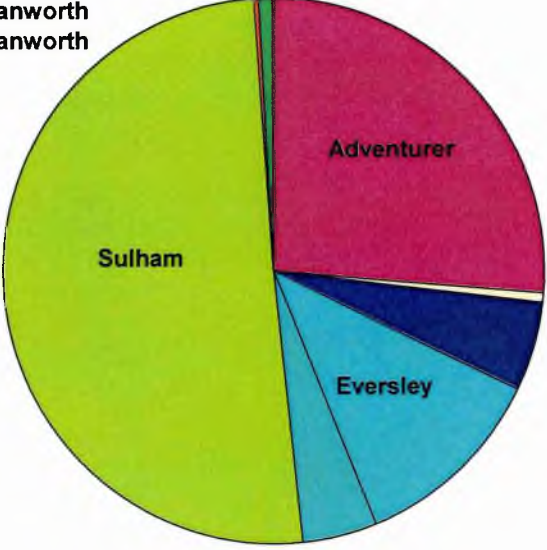
0554a
Frilford
Fyefield



0541A
Bearsted
Cottenham



0871c
Hanworth
Hanworth



- | | | | | |
|----------|-------------|----------|-----------|-------------|
| DistClay | Adventurers | Arrow | Ashley | Bearsted |
| Block | Bockmer | Colthrop | Cottenham | DistGravel |
| Drayton | Eversley | Evesham | Eyeworth | Faulkbourne |
| Fladbury | Hanslope | Hornbeam | Ickford | Lawford |
| Ludford | Marlow | Maxted | Newport | Oxpasture |
| Sonning | Sulham | Thames | Urban | Warden |
| Water | Waterstock | Wickham | Windrush | |

Appendix V

Tables show the percentage variance in surface soil moisture explained by SWRSS and SSWI for each of the eight sampling dates in Stone Hill, Church Meadow and Mox Farm for grid sizes of 20 m, 50 m and 100 m.

Stone Hill 2004

Grid Size	7th April 2004		21st May 2004		13th July 2004	
	SWRSS	SSWI	SWRSS	SSWI	SWRSS	SSWI
20 m	24	21	19	22	6	23
50 m	29	29	30	35	5	12
100 m	19	10	21	15	4	7

Church Meadow 2005

Grid Size	17 th June 2005		1 st July 2005		15 th July 2005	
	SWRSS	SSWI	SWRSS	SSWI	SWRSS	SSWI
20 m	14	15	14	14	11	9
50 m	15	22	13	15	13	14
100 m	11	22	14	16	13	17

Mox Farm 2005

Grid Size	10 th June 2005		11 th July 2005	
	SWRSS	SSWI	SWRSS	SSWI
20 m	N/S	3	4	N/S
50 m	N/S	3	7	N/S
100 m	N/S	N/S	N/S	N/S

Appendix VI

Spearman's Rank correlation matrices for soil moisture profile probe measurements for Stone Hill 2003, Stone Hill 2004 and Church Meadow 2003. Each measurement depth is analysed separately (100 mm, 200 mm, 300 mm, 400 mm, 600 mm, 1 m) Each matrix shows the Spearman's Rank Correlation Co-efficient between each date with every other date in the growing season sampled. Significant correlations at $P=0.05$ are shown in red.

Stone Hill 2003 100 mm

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03	
29-Apr-03	1.00	0.95	0.83	0.90	0.84	0.51	0.52	0.07	0.14	0.14	0.13	0.03	0.14	0.04	0.11	-0.03	0.01	0.07	0.13	0.24
7-May-03	0.95	1.00	0.86	0.86	0.89	0.53	0.48	0.12	0.16	0.16	0.14	0.04	0.23	0.04	0.13	-0.04	0.02	0.07	0.10	0.23
13-May-03	0.83	0.86	1.00	0.85	0.92	0.66	0.59	0.22	0.20	0.20	0.11	0.05	0.14	0.06	0.11	-0.07	-0.02	-0.03	0.29	0.21
20-May-03	0.90	0.86	0.85	1.00	0.84	0.51	0.57	0.27	0.23	0.23	0.24	0.15	0.28	0.13	0.18	0.03	0.08	0.15	0.33	0.26
28-May-03	0.84	0.89	0.92	0.84	1.00	0.70	0.68	0.28	0.24	0.24	0.16	0.07	0.20	0.09	0.18	-0.01	0.04	0.09	0.22	0.13
3-Jun-03	0.51	0.53	0.66	0.51	0.70	1.00	0.82	0.40	0.52	0.52	0.26	0.27	0.16	0.26	0.33	0.24	0.19	0.34	0.35	0.35
11-Jun-03	0.52	0.48	0.59	0.57	0.68	0.82	1.00	0.56	0.42	0.42	0.28	0.29	0.23	0.32	0.38	0.27	0.26	0.37	0.51	0.35
2-Jul-03	0.07	0.12	0.22	0.27	0.28	0.40	0.56	1.00	0.54	0.54	0.46	0.64	0.72	0.50	0.54	0.43	0.48	0.45	0.67	0.43
9-Jul-03	0.14	0.16	0.20	0.23	0.24	0.52	0.42	0.54	1.00	0.83	0.83	0.88	0.82	0.80	0.87	0.75	0.75	0.72	0.26	0.69
16-Jul-03	0.13	0.14	0.11	0.24	0.16	0.26	0.28	0.46	0.83	1.00	0.90	0.90	0.61	0.88	0.95	0.89	0.91	0.83	0.12	0.73
23-Jul-03	0.03	0.04	0.05	0.15	0.07	0.27	0.29	0.64	0.88	0.90	1.00	0.76	0.76	0.93	0.93	0.88	0.91	0.79	0.33	0.78
30-Jul-03	0.14	0.23	0.14	0.28	0.20	0.16	0.23	0.72	0.62	0.62	0.61	0.76	1.00	0.72	0.71	0.64	0.71	0.62	0.47	0.67
6-Aug-03	0.04	0.04	0.06	0.13	0.09	0.26	0.32	0.60	0.80	0.80	0.88	0.93	0.72	1.00	0.94	0.91	0.95	0.76	0.32	0.81
13-Aug-03	0.11	0.13	0.11	0.18	0.18	0.33	0.38	0.54	0.87	0.95	0.93	0.93	0.71	0.94	1.00	0.92	0.95	0.81	0.27	0.52
20-Aug-03	-0.03	-0.04	-0.07	0.03	-0.01	0.24	0.27	0.43	0.75	0.89	0.88	0.88	0.64	0.91	0.92	1.00	0.98	0.90	0.25	0.82
27-Aug-03	0.01	0.02	-0.02	0.08	0.04	0.19	0.26	0.48	0.75	0.91	0.91	0.91	0.71	0.95	0.95	0.98	1.00	0.86	0.27	0.83
4-Sep-03	0.07	0.07	-0.03	0.15	0.09	0.34	0.37	0.45	0.72	0.83	0.79	0.79	0.62	0.76	0.81	0.90	0.86	1.00	0.22	0.76
12-Sep-03	0.13	0.10	0.29	0.33	0.22	0.35	0.51	0.67	0.26	0.12	0.33	0.33	0.47	0.32	0.27	0.25	0.27	0.22	1.00	0.38
18-Sep-03	0.24	0.23	0.21	0.26	0.13	0.35	0.35	0.43	0.69	0.73	0.78	0.78	0.67	0.81	0.82	0.82	0.75	0.75	0.38	1.00

Stone Hill 2003 200 mm

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03
29-Apr-03	1.00	0.95	0.84	0.90	0.86	0.71	0.71	0.42	0.40	0.46	0.46	0.48	0.30	0.48	0.44	0.35	0.39	0.35	0.32
7-May-03	0.95	1.00	0.92	0.93	0.90	0.67	0.73	0.46	0.39	0.49	0.49	0.50	0.35	0.46	0.45	0.34	0.43	0.32	0.35
13-May-03	0.84	0.92	1.00	0.95	0.93	0.78	0.85	0.48	0.35	0.54	0.54	0.45	0.37	0.47	0.43	0.34	0.42	0.32	0.34
20-May-03	0.90	0.93	0.95	1.00	0.95	0.79	0.84	0.46	0.36	0.51	0.51	0.42	0.35	0.50	0.42	0.33	0.38	0.30	0.27
28-May-03	0.86	0.90	0.93	0.95	1.00	0.80	0.88	0.36	0.24	0.44	0.44	0.33	0.29	0.41	0.35	0.26	0.33	0.24	0.28
3-Jun-03	0.71	0.67	0.78	0.79	0.80	1.00	0.89	0.55	0.48	0.56	0.56	0.43	0.42	0.51	0.43	0.45	0.39	0.42	0.40
11-Jun-03	0.71	0.73	0.85	0.84	0.88	0.89	1.00	0.38	0.26	0.37	0.37	0.24	0.27	0.33	0.24	0.20	0.23	0.25	0.21
2-Jul-03	0.42	0.46	0.48	0.46	0.36	0.55	0.38	1.00	0.88	0.90	0.90	0.91	0.81	0.87	0.91	0.90	0.91	0.84	0.89
9-Jul-03	0.40	0.39	0.35	0.36	0.24	0.48	0.26	0.88	1.00	0.82	0.82	0.88	0.66	0.67	0.80	0.81	0.73	0.66	0.72
16-Jul-03	0.46	0.49	0.54	0.51	0.44	0.56	0.37	0.90	0.82	1.00	0.91	0.91	0.69	0.79	0.95	0.93	0.90	0.73	0.86
23-Jul-03	0.48	0.50	0.45	0.42	0.33	0.43	0.24	0.91	0.88	0.91	0.91	1.00	0.75	0.79	0.94	0.92	0.93	0.77	0.93
30-Jul-03	0.30	0.35	0.37	0.35	0.29	0.42	0.27	0.81	0.66	0.69	0.69	0.75	1.00	0.79	0.82	0.76	0.78	0.68	0.59
6-Aug-03	0.48	0.46	0.47	0.50	0.41	0.51	0.33	0.87	0.67	0.79	0.79	0.79	0.84	1.00	0.91	0.86	0.88	0.86	0.80
13-Aug-03	0.44	0.45	0.43	0.42	0.35	0.43	0.24	0.91	0.80	0.95	0.95	0.94	0.82	0.91	1.00	0.96	0.96	0.82	0.91
20-Aug-03	0.35	0.34	0.34	0.33	0.26	0.45	0.20	0.90	0.81	0.93	0.93	0.92	0.76	0.86	0.96	1.00	0.95	0.84	0.91
27-Aug-03	0.39	0.43	0.42	0.38	0.33	0.39	0.23	0.91	0.73	0.73	0.90	0.93	0.78	0.88	0.96	0.95	1.00	0.88	0.97
4-Sep-03	0.35	0.32	0.32	0.30	0.24	0.42	0.25	0.84	0.66	0.73	0.77	0.77	0.68	0.86	0.82	0.84	0.88	1.00	0.85
12-Sep-03	0.32	0.35	0.34	0.27	0.28	0.40	0.21	0.89	0.72	0.86	0.86	0.93	0.68	0.80	0.91	0.91	0.97	0.85	1.00
18-Sep-03	0.33	0.27	0.22	0.21	0.17	0.44	0.15	0.90	0.77	0.83	0.83	0.90	0.59	0.76	0.87	0.87	0.88	0.85	0.88

Stone Hill 2003 300 mm

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03	
29-Apr-03	1.00	0.98	0.96	0.97	0.97	0.90	0.96	0.73	0.72	0.72	0.73	0.80	0.79	0.76	0.84	0.71	0.67	0.80	0.79	0.76
7-May-03	0.98	1.00	0.94	0.96	0.97	0.91	0.95	0.74	0.72	0.72	0.74	0.82	0.82	0.81	0.86	0.75	0.71	0.87	0.79	0.78
13-May-03	0.96	0.94	1.00	0.99	0.96	0.90	0.96	0.66	0.73	0.73	0.78	0.77	0.73	0.73	0.85	0.68	0.66	0.75	0.80	0.71
20-May-03	0.97	0.96	0.99	1.00	0.99	0.93	0.98	0.71	0.74	0.79	0.78	0.77	0.75	0.86	0.72	0.69	0.80	0.81	0.74	0.74
28-May-03	0.97	0.97	0.98	0.99	1.00	0.94	0.97	0.70	0.75	0.77	0.77	0.77	0.76	0.75	0.86	0.73	0.70	0.81	0.81	0.73
3-Jun-03	0.90	0.91	0.90	0.93	0.94	1.00	0.95	0.65	0.75	0.68	0.65	0.65	0.69	0.65	0.74	0.70	0.63	0.75	0.75	0.67
11-Jun-03	0.96	0.95	0.96	0.98	0.97	0.95	1.00	0.73	0.77	0.77	0.78	0.76	0.79	0.76	0.83	0.71	0.69	0.83	0.77	0.71
2-Jul-03	0.73	0.74	0.66	0.71	0.70	0.65	0.73	1.00	0.79	0.77	0.85	0.87	0.82	0.83	0.83	0.84	0.73	0.77	0.78	0.78
9-Jul-03	0.72	0.72	0.73	0.74	0.75	0.75	0.77	0.79	1.00	0.80	0.78	0.86	0.84	0.82	0.82	0.79	0.75	0.84	0.70	0.70
16-Jul-03	0.73	0.74	0.78	0.79	0.77	0.68	0.78	0.77	0.80	1.00	0.90	0.90	0.83	0.86	0.93	0.82	0.88	0.78	0.76	0.74
23-Jul-03	0.80	0.82	0.77	0.78	0.77	0.65	0.76	0.85	0.78	0.86	0.90	1.00	0.90	0.93	0.95	0.86	0.85	0.87	0.89	0.89
30-Jul-03	0.79	0.82	0.73	0.77	0.76	0.69	0.79	0.87	0.86	0.83	0.90	1.00	0.97	0.92	0.88	0.86	0.88	0.85	0.84	0.84
6-Aug-03	0.76	0.81	0.73	0.75	0.75	0.65	0.76	0.82	0.84	0.86	0.93	0.97	1.00	0.93	0.87	0.90	0.84	0.81	0.81	0.81
13-Aug-03	0.84	0.86	0.85	0.86	0.86	0.74	0.83	0.83	0.82	0.93	0.95	0.92	0.93	1.00	0.91	0.91	0.85	0.90	0.88	0.88
20-Aug-03	0.71	0.75	0.68	0.72	0.73	0.70	0.71	0.83	0.82	0.82	0.86	0.88	0.87	0.91	1.00	0.96	0.79	0.93	0.96	0.96
27-Aug-03	0.67	0.71	0.66	0.69	0.70	0.63	0.69	0.84	0.79	0.88	0.88	0.86	0.87	0.91	0.96	1.00	0.81	0.84	0.89	0.89
4-Sep-03	0.80	0.87	0.75	0.80	0.81	0.75	0.83	0.73	0.75	0.78	0.85	0.85	0.90	0.85	0.79	0.81	1.00	0.72	0.69	0.69
12-Sep-03	0.79	0.79	0.80	0.81	0.81	0.75	0.77	0.77	0.84	0.84	0.76	0.87	0.86	0.84	0.90	0.93	0.84	0.72	1.00	0.94
18-Sep-03	0.76	0.78	0.71	0.74	0.73	0.67	0.71	0.78	0.70	0.74	0.89	0.84	0.81	0.88	0.96	0.89	0.69	0.94	1.00	1.00

Stone Hill 2003 400 mm

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03
29-Apr-03	1.00	0.98	0.96	0.96	0.95	0.92	0.91	0.75	0.74	0.80	0.73	0.81	0.79	0.77	0.77	0.81	0.86	0.78	0.69
7-May-03	0.96	1.00	0.96	0.98	0.98	0.93	0.93	0.72	0.73	0.73	0.82	0.74	0.78	0.79	0.82	0.85	0.71	0.80	0.78
13-May-03	0.96	0.96	1.00	0.97	0.96	0.94	0.94	0.75	0.75	0.84	0.77	0.83	0.78	0.80	0.80	0.84	0.69	0.78	0.76
20-May-03	0.96	0.98	0.97	1.00	0.98	0.94	0.93	0.73	0.73	0.84	0.73	0.81	0.78	0.79	0.80	0.84	0.68	0.78	0.69
28-May-03	0.95	0.98	0.96	0.98	1.00	0.93	0.93	0.70	0.74	0.81	0.74	0.83	0.78	0.81	0.82	0.85	0.72	0.79	0.71
3-Jun-03	0.92	0.93	0.94	0.94	0.93	1.00	0.95	0.81	0.79	0.86	0.81	0.85	0.82	0.84	0.87	0.89	0.75	0.82	0.77
11-Jun-03	0.91	0.93	0.94	0.93	0.93	0.95	1.00	0.81	0.73	0.83	0.80	0.81	0.76	0.81	0.82	0.86	0.74	0.78	0.74
2-Jul-03	0.75	0.72	0.75	0.73	0.70	0.81	0.81	1.00	0.81	0.79	0.82	0.83	0.82	0.83	0.80	0.82	0.79	0.81	0.74
9-Jul-03	0.74	0.73	0.75	0.73	0.74	0.79	0.73	0.81	1.00	0.92	0.93	0.95	0.97	0.97	0.90	0.90	0.91	0.95	0.92
16-Jul-03	0.80	0.82	0.84	0.84	0.81	0.86	0.83	0.79	0.92	1.00	0.91	0.97	0.93	0.94	0.90	0.92	0.88	0.90	0.86
23-Jul-03	0.73	0.74	0.77	0.73	0.74	0.81	0.80	0.82	0.93	0.91	1.00	0.93	0.95	0.97	0.93	0.94	0.93	0.91	0.94
30-Jul-03	0.81	0.82	0.83	0.81	0.83	0.85	0.81	0.83	0.95	0.97	0.93	1.00	0.96	0.97	0.94	0.94	0.94	0.94	0.92
6-Aug-03	0.79	0.78	0.78	0.78	0.78	0.82	0.76	0.82	0.97	0.93	0.95	0.96	1.00	0.96	0.94	0.93	0.90	0.96	0.93
13-Aug-03	0.77	0.79	0.80	0.79	0.81	0.84	0.81	0.83	0.97	0.94	0.97	0.97	0.96	1.00	0.95	0.95	0.94	0.94	0.93
20-Aug-03	0.77	0.82	0.80	0.80	0.82	0.87	0.82	0.80	0.90	0.90	0.93	0.94	0.94	0.95	1.00	0.98	0.92	0.97	0.93
27-Aug-03	0.81	0.85	0.84	0.84	0.85	0.89	0.86	0.82	0.90	0.92	0.94	0.94	0.94	0.95	0.98	1.00	0.90	0.96	0.95
4-Sep-03	0.66	0.71	0.69	0.68	0.72	0.75	0.74	0.79	0.91	0.88	0.93	0.94	0.90	0.94	0.92	0.90	1.00	0.93	0.95
12-Sep-03	0.76	0.80	0.78	0.78	0.79	0.82	0.78	0.81	0.95	0.90	0.91	0.94	0.96	0.94	0.97	0.96	0.93	1.00	0.94
18-Sep-03	0.69	0.76	0.76	0.69	0.71	0.77	0.74	0.74	0.92	0.86	0.94	0.92	0.93	0.93	0.93	0.95	0.95	0.94	1.00

Stone Hill 2003 600 mm

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03
29-Apr-03	1.00	0.99	0.98	0.99	0.99	0.98	0.98	0.82	0.89	0.88	0.92	0.88	0.93	0.91	0.92	0.93	0.67	0.90	0.93
7-May-03	0.99	1.00	0.98	0.99	0.99	0.98	0.98	0.83	0.89	0.89	0.92	0.88	0.92	0.91	0.92	0.91	0.68	0.89	0.92
13-May-03	0.98	0.98	1.00	0.99	0.99	0.98	0.98	0.80	0.91	0.90	0.93	0.88	0.94	0.92	0.95	0.94	0.69	0.93	0.91
20-May-03	0.99	0.99	0.99	1.00	0.99	1.00	0.99	0.82	0.91	0.91	0.93	0.89	0.93	0.93	0.94	0.94	0.66	0.91	0.91
28-May-03	0.99	0.99	0.99	0.99	1.00	0.98	0.99	0.80	0.90	0.88	0.92	0.87	0.92	0.90	0.93	0.92	0.71	0.90	0.91
3-Jun-03	0.98	0.98	0.98	1.00	0.98	1.00	0.99	0.83	0.93	0.91	0.93	0.90	0.93	0.92	0.94	0.94	0.71	0.92	0.91
11-Jun-03	0.98	0.98	0.99	0.99	0.99	0.99	1.00	0.92	0.92	0.92	0.94	0.89	0.92	0.92	0.93	0.94	0.75	0.92	0.90
2-Jul-03	0.82	0.83	0.80	0.82	0.80	0.83	0.83	1.00	0.92	0.94	0.92	0.94	0.92	0.92	0.87	0.87	0.74	0.89	0.87
9-Jul-03	0.89	0.89	0.91	0.91	0.91	0.93	0.92	0.92	1.00	0.96	0.98	0.99	0.96	0.97	0.97	0.95	0.78	0.97	0.93
16-Jul-03	0.88	0.89	0.90	0.91	0.88	0.91	0.92	0.94	0.96	1.00	0.98	0.99	0.99	0.99	0.96	0.97	0.81	0.96	0.92
23-Jul-03	0.92	0.92	0.93	0.93	0.92	0.93	0.94	0.92	0.94	0.98	1.00	0.97	0.97	0.98	0.97	0.97	0.77	0.97	0.95
30-Jul-03	0.88	0.88	0.88	0.89	0.87	0.90	0.89	0.94	0.97	0.99	0.97	1.00	0.97	0.98	0.97	0.97	0.76	0.96	0.93
6-Aug-03	0.93	0.92	0.94	0.93	0.92	0.92	0.92	0.92	0.98	0.96	0.97	0.97	1.00	0.97	0.97	0.96	0.75	0.98	0.96
13-Aug-03	0.91	0.91	0.92	0.93	0.90	0.92	0.92	0.92	0.97	0.99	0.98	0.98	0.97	1.00	0.97	0.97	0.75	0.98	0.96
20-Aug-03	0.92	0.92	0.95	0.94	0.93	0.94	0.93	0.87	0.97	0.96	0.97	0.97	0.97	0.97	1.00	0.97	0.72	0.97	0.92
27-Aug-03	0.93	0.91	0.94	0.94	0.92	0.94	0.94	0.87	0.95	0.97	0.97	0.97	0.96	0.97	0.98	1.00	0.75	0.96	0.94
4-Sep-03	0.67	0.68	0.69	0.66	0.71	0.71	0.75	0.74	0.78	0.72	0.77	0.76	0.75	0.75	0.72	0.75	1.00	0.75	0.75
12-Sep-03	0.90	0.89	0.93	0.91	0.90	0.92	0.92	0.89	0.97	0.96	0.97	0.96	0.98	0.98	0.97	0.96	0.75	1.00	0.96
18-Sep-03	0.93	0.92	0.91	0.91	0.91	0.91	0.90	0.87	0.93	0.92	0.95	0.93	0.96	0.96	0.92	0.94	0.75	0.96	1.00

Stone Hill 2003 1 m

Variable	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03	30-Jul-03	6-Aug-03	13-Aug-03	20-Aug-03	27-Aug-03	4-Sep-03	12-Sep-03	18-Sep-03
29-Apr-03	1.00	0.98	0.98	0.98	0.98	0.97	0.97	0.99	0.78	0.96	0.94	0.94	0.92	0.92	0.89	0.89	0.90	0.84	0.93
7-May-03	0.98	1.00	0.97	0.98	0.98	0.98	0.98	0.97	0.80	0.94	0.92	0.93	0.91	0.90	0.88	0.88	0.88	0.81	0.89
13-May-03	0.98	0.97	1.00	0.96	0.97	0.98	0.98	0.98	0.77	0.94	0.93	0.95	0.91	0.91	0.87	0.88	0.86	0.82	0.89
20-May-03	0.98	0.98	0.96	1.00	0.99	0.96	0.96	0.99	0.74	0.96	0.96	0.95	0.93	0.93	0.89	0.89	0.89	0.82	0.90
28-May-03	0.98	0.98	0.97	0.99	1.00	0.97	0.99	0.99	0.75	0.96	0.95	0.95	0.93	0.93	0.89	0.89	0.88	0.82	0.90
3-Jun-03	0.97	0.99	0.98	0.96	0.97	1.00	0.96	0.96	0.79	0.94	0.92	0.93	0.89	0.89	0.86	0.87	0.86	0.81	0.89
11-Jun-03	0.99	0.97	0.98	0.99	0.99	0.96	1.00	0.97	0.76	0.97	0.96	0.96	0.94	0.95	0.91	0.91	0.90	0.84	0.92
2-Jul-03	0.78	0.80	0.77	0.74	0.75	0.79	0.76	1.00	0.75	0.75	0.76	0.78	0.81	0.77	0.85	0.85	0.87	0.82	0.80
9-Jul-03	0.96	0.94	0.94	0.96	0.96	0.94	0.97	0.75	1.00	0.97	0.97	0.97	0.95	0.96	0.93	0.93	0.93	0.85	0.96
16-Jul-03	0.94	0.93	0.93	0.95	0.95	0.92	0.96	0.76	0.97	1.00	0.99	0.99	0.95	0.95	0.92	0.92	0.90	0.88	0.92
23-Jul-03	0.94	0.93	0.95	0.95	0.95	0.93	0.96	0.78	0.97	0.97	0.99	1.00	0.97	0.97	0.94	0.94	0.91	0.85	0.91
30-Jul-03	0.92	0.91	0.91	0.93	0.93	0.89	0.94	0.81	0.95	0.95	0.95	0.97	1.00	0.99	0.96	0.96	0.94	0.90	0.94
6-Aug-03	0.92	0.90	0.91	0.93	0.93	0.89	0.95	0.77	0.96	0.96	0.95	0.97	0.99	1.00	0.96	0.96	0.94	0.89	0.95
13-Aug-03	0.89	0.88	0.87	0.89	0.89	0.86	0.91	0.85	0.93	0.93	0.92	0.94	0.96	0.96	1.00	0.99	0.98	0.89	0.93
20-Aug-03	0.89	0.88	0.88	0.89	0.89	0.87	0.91	0.85	0.93	0.93	0.92	0.94	0.96	0.96	0.99	1.00	0.97	0.88	0.94
27-Aug-03	0.90	0.88	0.86	0.89	0.88	0.86	0.90	0.87	0.93	0.93	0.90	0.91	0.94	0.90	0.98	0.97	1.00	0.91	0.96
4-Sep-03	0.84	0.81	0.82	0.82	0.82	0.81	0.84	0.82	0.85	0.85	0.88	0.85	0.90	0.89	0.89	0.88	0.91	1.00	0.89
12-Sep-03	0.93	0.89	0.89	0.90	0.90	0.89	0.92	0.80	0.96	0.96	0.92	0.91	0.92	0.94	0.93	0.94	0.96	0.89	1.00
18-Sep-03	0.93	0.91	0.89	0.92	0.90	0.91	0.93	0.90	0.95	0.95	0.93	0.94	0.94	0.95	0.97	0.97	0.98	0.92	0.99

Church Meadow 2003 100 mm

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.94	0.73	0.74	0.63	0.61	0.57	0.60	0.60	0.60	0.31	0.24	0.30	0.32	0.31
8-Apr-03	0.94	1.00	0.75	0.72	0.58	0.58	0.56	0.64	0.69	0.69	0.29	0.32	0.34	0.35	0.41
15-Apr-03	0.73	0.75	1.00	0.93	0.75	0.92	0.86	0.81	0.84	0.84	0.60	0.60	0.69	0.61	0.78
22-Apr-03	0.74	0.72	0.93	1.00	0.85	0.84	0.89	0.86	0.92	0.92	0.73	0.64	0.74	0.60	0.73
29-Apr-03	0.63	0.58	0.75	0.85	1.00	0.70	0.82	0.73	0.74	0.74	0.66	0.70	0.62	0.78	0.67
7-May-03	0.61	0.58	0.92	0.84	0.70	1.00	0.89	0.69	0.76	0.76	0.69	0.56	0.70	0.63	0.75
13-May-03	0.57	0.56	0.86	0.89	0.82	0.89	1.00	0.83	0.83	0.83	0.72	0.64	0.80	0.67	0.77
20-May-03	0.60	0.64	0.81	0.86	0.73	0.69	0.83	1.00	0.85	0.85	0.49	0.61	0.60	0.47	0.63
28-May-03	0.60	0.69	0.84	0.92	0.74	0.76	0.83	0.85	1.00	1.00	0.77	0.65	0.73	0.58	0.76
3-Jun-03	0.31	0.29	0.60	0.73	0.66	0.69	0.72	0.49	0.77	0.77	1.00	0.67	0.87	0.59	0.70
11-Jun-03	0.50	0.46	0.72	0.85	0.78	0.66	0.76	0.79	0.77	0.77	0.77	0.74	0.79	0.65	0.76
2-Jul-03	0.24	0.32	0.60	0.64	0.70	0.56	0.64	0.61	0.65	0.65	0.67	1.00	0.78	0.77	0.86
9-Jul-03	0.30	0.34	0.69	0.74	0.62	0.70	0.80	0.60	0.73	0.73	0.87	0.78	1.00	0.67	0.86
16-Jul-03	0.32	0.35	0.61	0.60	0.78	0.63	0.67	0.47	0.58	0.59	0.59	0.77	0.67	1.00	0.80
23-Jul-03	0.31	0.41	0.78	0.73	0.67	0.75	0.77	0.63	0.76	0.70	0.70	0.86	0.86	0.80	1.00

Church Meadow 2003 200 mm

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.92	0.88	0.92	0.89	0.75	0.75	0.82	0.73	0.74	0.78	0.75	0.33	0.62	0.35
8-Apr-03	0.92	1.00	0.96	0.95	0.95	0.92	0.92	0.91	0.87	0.84	0.89	0.84	0.45	0.79	0.46
15-Apr-03	0.88	0.96	1.00	0.94	0.88	0.86	0.86	0.85	0.82	0.78	0.82	0.74	0.37	0.70	0.41
22-Apr-03	0.92	0.95	0.94	1.00	0.96	0.85	0.85	0.89	0.77	0.78	0.84	0.74	0.45	0.82	0.57
29-Apr-03	0.89	0.95	0.88	0.96	1.00	0.90	0.90	0.96	0.87	0.89	0.92	0.86	0.52	0.87	0.56
7-May-03	0.75	0.92	0.86	0.85	0.90	1.00	1.00	0.94	0.96	0.93	0.94	0.93	0.46	0.80	0.54
13-May-03	0.82	0.91	0.85	0.89	0.96	0.94	0.94	1.00	0.95	0.97	0.97	0.94	0.53	0.87	0.60
20-May-03	0.73	0.87	0.82	0.77	0.87	0.96	0.96	0.95	1.00	0.98	0.96	0.96	0.46	0.74	0.46
28-May-03	0.74	0.84	0.78	0.78	0.89	0.93	0.93	0.97	0.98	1.00	0.97	0.97	0.50	0.78	0.56
3-Jun-03	0.78	0.89	0.82	0.84	0.92	0.94	0.94	0.97	0.96	0.97	1.00	0.95	0.58	0.82	0.62
11-Jun-03	0.75	0.84	0.74	0.74	0.86	0.93	0.93	0.94	0.96	0.97	0.95	1.00	0.44	0.72	0.54
2-Jul-03	0.33	0.45	0.37	0.45	0.52	0.46	0.53	0.46	0.46	0.50	0.58	0.44	1.00	0.79	0.61
9-Jul-03	0.62	0.79	0.70	0.82	0.87	0.80	0.87	0.87	0.74	0.78	0.82	0.72	1.00	0.71	0.71
16-Jul-03	0.35	0.46	0.41	0.57	0.56	0.54	0.60	0.60	0.46	0.56	0.62	0.54	0.61	0.71	1.00
23-Jul-03	0.54	0.76	0.69	0.78	0.79	0.84	0.83	0.83	0.75	0.77	0.84	0.72	0.75	0.93	0.78

Church meadow 2003 300 mm

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.98	0.96	0.94	0.84	0.92	0.87	0.86	0.81	0.90	0.87	0.56	0.66	0.51	0.63
8-Apr-03	0.98	1.00	0.95	0.96	0.80	0.90	0.86	0.86	0.83	0.91	0.86	0.59	0.69	0.56	0.66
15-Apr-03	0.96	0.95	1.00	0.88	0.88	0.91	0.87	0.85	0.82	0.86	0.83	0.48	0.58	0.46	0.60
22-Apr-03	0.94	0.96	0.88	1.00	0.77	0.87	0.86	0.88	0.87	0.94	0.86	0.64	0.73	0.60	0.70
29-Apr-03	0.84	0.80	0.88	0.77	1.00	0.91	0.85	0.87	0.78	0.79	0.79	0.52	0.60	0.54	0.68
7-May-03	0.92	0.90	0.91	0.87	0.91	1.00	0.88	0.93	0.89	0.91	0.87	0.66	0.76	0.67	0.77
13-May-03	0.87	0.86	0.87	0.86	0.85	0.88	1.00	0.93	0.92	0.94	0.95	0.60	0.61	0.55	0.73
20-May-03	0.86	0.86	0.85	0.88	0.87	0.93	0.93	1.00	0.94	0.93	0.93	0.73	0.72	0.70	0.82
28-May-03	0.81	0.83	0.82	0.87	0.78	0.89	0.92	0.94	1.00	0.93	0.91	0.70	0.70	0.67	0.78
3-Jun-03	0.90	0.91	0.86	0.94	0.79	0.91	0.94	0.93	0.93	1.00	0.90	0.70	0.72	0.63	0.77
11-Jun-03	0.87	0.86	0.83	0.86	0.79	0.87	0.95	0.93	0.91	0.90	1.00	0.66	0.61	0.58	0.71
2-Jul-03	0.56	0.59	0.48	0.64	0.52	0.66	0.60	0.73	0.70	0.70	0.66	1.00	0.88	0.91	0.91
9-Jul-03	0.66	0.69	0.58	0.73	0.60	0.76	0.61	0.72	0.70	0.72	0.61	0.88	1.00	0.93	0.91
16-Jul-03	0.51	0.56	0.46	0.60	0.54	0.67	0.55	0.70	0.67	0.63	0.58	0.91	0.93	1.00	0.95
23-Jul-03	0.63	0.66	0.60	0.70	0.68	0.77	0.73	0.82	0.78	0.77	0.71	0.91	0.91	0.95	1.00

Church Meadow 2003 400 mm

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.97	0.91	0.86	0.88	0.84	0.83	0.85	0.81	0.83	0.83	0.61	0.67	0.64	0.76
8-Apr-03	0.97	1.00	0.93	0.88	0.86	0.82	0.83	0.84	0.80	0.85	0.84	0.59	0.57	0.67	0.77
15-Apr-03	0.91	0.93	1.00	0.92	0.92	0.85	0.87	0.90	0.83	0.85	0.88	0.38	0.48	0.45	0.65
22-Apr-03	0.86	0.88	0.92	1.00	0.96	0.92	0.91	0.91	0.92	0.90	0.85	0.45	0.51	0.46	0.74
29-Apr-03	0.88	0.86	0.92	0.96	1.00	0.97	0.96	0.95	0.94	0.91	0.90	0.47	0.63	0.47	0.75
7-May-03	0.84	0.82	0.85	0.92	0.97	1.00	0.99	0.97	0.97	0.96	0.93	0.52	0.70	0.46	0.72
13-May-03	0.83	0.83	0.87	0.91	0.96	0.99	1.00	0.97	0.95	0.96	0.95	0.53	0.69	0.50	0.74
20-May-03	0.85	0.84	0.90	0.91	0.95	0.97	0.97	1.00	0.97	0.96	0.97	0.44	0.65	0.41	0.67
28-May-03	0.81	0.80	0.83	0.92	0.94	0.97	0.95	0.97	1.00	0.97	0.93	0.50	0.67	0.45	0.73
3-Jun-03	0.83	0.85	0.85	0.90	0.91	0.96	0.96	0.96	0.97	1.00	0.97	0.54	0.66	0.51	0.74
11-Jun-03	0.83	0.84	0.88	0.85	0.90	0.93	0.95	0.97	0.93	0.97	1.00	0.47	0.62	0.45	0.66
2-Jul-03	0.61	0.59	0.38	0.45	0.47	0.52	0.53	0.44	0.50	0.54	0.47	1.00	0.84	0.94	0.86
9-Jul-03	0.67	0.57	0.48	0.51	0.63	0.70	0.69	0.65	0.67	0.66	0.62	0.84	1.00	0.76	0.77
16-Jul-03	0.64	0.67	0.45	0.46	0.47	0.46	0.50	0.41	0.45	0.51	0.45	0.94	0.76	1.00	0.92
23-Jul-03	0.76	0.77	0.65	0.74	0.75	0.72	0.74	0.67	0.73	0.74	0.66	0.86	0.77	0.92	1.00

Church Meadow 2003 600 mm

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.99	0.97	0.99	0.98	0.98	0.99	0.96	0.98	0.96	0.97	0.94	0.95	0.95	0.96
8-Apr-03	0.99	1.00	0.99	0.98	0.98	0.98	0.99	0.97	0.97	0.96	0.96	0.88	0.97	0.93	0.94
15-Apr-03	0.97	0.99	1.00	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.94	0.87	0.96	0.92	0.94
22-Apr-03	0.99	0.98	0.99	1.00	0.99	0.99	0.99	0.96	0.99	0.97	0.95	0.92	0.94	0.94	0.95
29-Apr-03	0.98	0.98	0.99	0.99	1.00	0.97	0.97	0.99	0.98	0.97	0.94	0.88	0.93	0.91	0.92
7-May-03	0.99	0.99	0.98	0.99	0.97	1.00	0.96	0.96	0.99	0.97	0.97	0.91	0.96	0.95	0.96
13-May-03	0.96	0.97	0.98	0.98	0.99	0.96	0.99	1.00	0.97	0.96	0.94	0.84	0.95	0.89	0.90
20-May-03	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.97	0.99	0.98	0.97	0.91	0.95	0.95	0.96
28-May-03	0.98	0.97	0.98	0.99	0.98	0.98	0.98	0.97	1.00	0.99	0.97	0.92	0.96	0.95	0.96
3-Jun-03	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.96	0.98	1.00	0.97	0.89	0.97	0.91	0.93
11-Jun-03	0.97	0.96	0.94	0.95	0.94	0.97	0.97	0.94	0.97	0.97	1.00	0.91	0.96	0.93	0.92
2-Jul-03	0.94	0.88	0.87	0.92	0.88	0.91	0.96	0.84	0.91	0.92	0.91	1.00	0.86	0.96	0.95
9-Jul-03	0.95	0.97	0.96	0.94	0.93	0.96	0.95	0.95	0.96	0.97	0.96	0.86	1.00	0.90	0.92
16-Jul-03	0.95	0.93	0.92	0.94	0.91	0.95	0.95	0.89	0.95	0.91	0.93	0.96	0.90	1.00	0.97
23-Jul-03	0.96	0.94	0.94	0.95	0.92	0.96	0.96	0.90	0.96	0.93	0.92	0.95	0.92	0.97	1.00

Church Meadow 2003 1 m

Variable	1-Apr-03	8-Apr-03	15-Apr-03	22-Apr-03	29-Apr-03	7-May-03	13-May-03	20-May-03	28-May-03	3-Jun-03	11-Jun-03	2-Jul-03	9-Jul-03	16-Jul-03	23-Jul-03
1-Apr-03	1.00	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.94	0.94	0.87	0.89	0.89
8-Apr-03	0.98	1.00	0.97	0.97	0.98	0.98	0.98	0.98	0.97	0.97	0.94	0.93	0.86	0.88	0.88
15-Apr-03	0.99	0.97	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.94	0.95	0.87	0.89	0.90
22-Apr-03	0.99	0.97	0.99	1.00	0.99	0.98	0.98	0.99	0.98	0.98	0.94	0.94	0.87	0.90	0.89
29-Apr-03	0.99	0.98	0.99	0.99	1.00	0.99	0.99	0.99	0.98	0.99	0.94	0.95	0.88	0.90	0.91
7-May-03	0.99	0.98	0.99	0.98	0.99	1.00	1.00	1.00	1.00	1.00	0.96	0.97	0.88	0.92	0.90
13-May-03	0.99	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.96	0.97	0.88	0.92	0.90
20-May-03	0.98	0.97	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	0.98	0.98	0.89	0.93	0.91
28-May-03	0.99	0.97	0.99	0.98	0.99	1.00	1.00	1.00	1.00	1.00	0.97	0.98	0.89	0.93	0.91
3-Jun-03	0.94	0.94	0.94	0.94	0.94	0.96	0.96	0.96	0.98	0.97	1.00	1.00	0.90	0.95	0.88
11-Jun-03	0.94	0.93	0.95	0.94	0.95	0.97	0.97	0.97	0.98	1.00	1.00	1.00	0.91	0.96	0.89
2-Jul-03	0.87	0.86	0.87	0.87	0.88	0.88	0.88	0.88	0.89	0.90	0.90	1.00	1.00	0.96	0.97
9-Jul-03	0.89	0.88	0.89	0.90	0.90	0.92	0.92	0.92	0.93	0.95	0.96	0.96	1.00	1.00	0.94
16-Jul-03	0.91	0.90	0.91	0.91	0.92	0.91	0.91	0.91	0.91	0.87	0.88	0.88	0.97	0.92	0.98
23-Jul-03	0.89	0.88	0.90	0.89	0.91	0.90	0.90	0.90	0.91	0.88	0.89	0.89	0.97	0.94	1.00

Stone Hill 2004 100mm

Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.94	0.82	0.67	0.82	0.84	0.84	0.84	0.82	0.76	0.74	0.76	0.67	0.70	0.60	0.33
15-Apr-04	0.94	1.00	0.82	0.74	0.85	0.86	0.90	0.90	0.85	0.76	0.71	0.77	0.70	0.74	0.74	0.45
23-Apr-04	0.82	0.82	1.00	0.67	0.80	0.94	0.87	0.87	0.92	0.81	0.84	0.85	0.71	0.81	0.68	0.34
6-May-04	0.67	0.74	0.67	1.00	0.88	0.75	0.70	0.70	0.63	0.53	0.43	0.50	0.55	0.55	0.48	0.11
10-May-04	0.82	0.85	0.80	0.88	1.00	0.82	0.85	0.85	0.78	0.65	0.57	0.60	0.59	0.57	0.53	0.12
14-May-04	0.84	0.86	0.94	0.75	0.82	1.00	0.89	0.89	0.95	0.88	0.86	0.87	0.81	0.87	0.76	0.41
21-May-04	0.84	0.90	0.87	0.70	0.85	0.89	1.00	1.00	0.90	0.83	0.79	0.79	0.79	0.77	0.75	0.43
7-Jun-04	0.82	0.85	0.92	0.63	0.78	0.95	0.90	0.90	1.00	0.90	0.89	0.90	0.83	0.89	0.79	0.49
11-Jun-04	0.76	0.76	0.81	0.53	0.65	0.88	0.83	0.83	0.90	1.00	0.97	0.86	0.86	0.86	0.75	0.53
18-Jun-04	0.74	0.71	0.84	0.43	0.57	0.86	0.79	0.79	0.89	0.97	1.00	0.86	0.83	0.86	0.73	0.55
25-Jun-04	0.76	0.77	0.85	0.50	0.60	0.87	0.79	0.79	0.90	0.86	0.86	1.00	0.81	0.93	0.79	0.64
2-Jul-04	0.67	0.70	0.71	0.55	0.59	0.81	0.79	0.79	0.83	0.86	0.83	0.81	1.00	0.92	0.85	0.67
8-Jul-04	0.70	0.74	0.81	0.55	0.57	0.87	0.77	0.77	0.89	0.86	0.86	0.93	0.92	1.00	0.86	0.70
23-Jul-04	0.60	0.74	0.68	0.48	0.53	0.76	0.75	0.75	0.79	0.75	0.73	0.79	0.85	0.86	1.00	0.83
30-Jul-04	0.33	0.45	0.34	0.11	0.12	0.41	0.43	0.43	0.49	0.53	0.55	0.64	0.67	0.70	0.83	1.00
6-Aug-04	0.48	0.61	0.52	0.41	0.43	0.64	0.62	0.62	0.62	0.61	0.59	0.66	0.76	0.75	0.89	1.00

Stone Hill 2004 200 mm

Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.96	0.92	0.59	0.83	0.77	0.84	0.86	0.82	0.82	0.82	0.89	0.78	0.73	0.60	0.67
15-Apr-04	0.96	1.00	0.94	0.57	0.86	0.83	0.86	0.87	0.82	0.84	0.88	0.90	0.80	0.77	0.66	0.73
23-Apr-04	0.92	0.94	1.00	0.64	0.88	0.84	0.88	0.91	0.85	0.85	0.90	0.89	0.79	0.75	0.61	0.65
6-May-04	0.59	0.57	0.64	1.00	0.74	0.72	0.73	0.67	0.66	0.73	0.58	0.70	0.51	0.46	0.35	0.26
10-May-04	0.83	0.86	0.88	0.74	1.00	0.97	0.95	0.89	0.90	0.90	0.84	0.87	0.75	0.74	0.54	0.60
14-May-04	0.77	0.83	0.84	0.72	0.97	1.00	0.94	0.87	0.89	0.88	0.81	0.84	0.65	0.65	0.40	0.48
21-May-04	0.84	0.86	0.88	0.73	0.95	0.94	1.00	0.94	0.96	0.95	0.78	0.87	0.62	0.62	0.41	0.45
7-Jun-04	0.86	0.87	0.91	0.67	0.89	0.87	0.94	1.00	0.96	0.96	0.85	0.93	0.65	0.69	0.52	0.54
11-Jun-04	0.82	0.82	0.85	0.66	0.90	0.89	0.96	0.96	1.00	0.94	0.80	0.88	0.60	0.61	0.40	0.45
18-Jun-04	0.82	0.84	0.85	0.73	0.90	0.88	0.95	0.96	0.94	1.00	0.82	0.91	0.59	0.61	0.45	0.48
25-Jun-04	0.82	0.88	0.90	0.58	0.84	0.81	0.78	0.85	0.80	0.82	1.00	0.88	0.83	0.78	0.67	0.72
2-Jul-04	0.89	0.90	0.89	0.70	0.87	0.84	0.87	0.93	0.88	0.91	0.88	1.00	0.78	0.82	0.70	0.70
8-Jul-04	0.78	0.80	0.79	0.51	0.75	0.65	0.62	0.65	0.60	0.59	0.83	0.78	1.00	0.86	0.81	0.84
23-Jul-04	0.73	0.77	0.75	0.46	0.74	0.65	0.62	0.69	0.61	0.61	0.78	0.82	0.86	1.00	0.93	0.94
30-Jul-04	0.60	0.66	0.61	0.35	0.54	0.40	0.41	0.52	0.40	0.45	0.67	0.70	0.81	0.93	1.00	0.96
6-Aug-04	0.67	0.73	0.65	0.26	0.60	0.48	0.45	0.54	0.45	0.48	0.72	0.70	0.84	0.94	0.96	1.00

Stone Hill 2004 300 mm

Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.93	0.95	0.71	0.87	0.87	0.89	0.92	0.92	0.90	0.94	0.90	0.93	0.85	0.86	0.89
15-Apr-04	0.93	1.00	0.98	0.82	0.96	0.96	0.95	0.96	0.93	0.90	0.92	0.93	0.90	0.84	0.83	0.82
23-Apr-04	0.95	0.98	1.00	0.80	0.97	0.96	0.96	0.97	0.95	0.94	0.96	0.95	0.94	0.86	0.86	0.86
6-May-04	0.71	0.82	0.80	1.00	0.81	0.86	0.85	0.82	0.75	0.76	0.73	0.79	0.74	0.74	0.74	0.72
10-May-04	0.87	0.96	0.97	0.81	1.00	0.94	0.94	0.94	0.90	0.90	0.91	0.90	0.90	0.85	0.84	0.84
14-May-04	0.87	0.96	0.96	0.86	0.94	1.00	0.99	0.94	0.94	0.93	0.93	0.97	0.90	0.84	0.83	0.80
21-May-04	0.89	0.95	0.96	0.85	0.94	0.99	1.00	0.94	0.96	0.96	0.95	0.96	0.94	0.86	0.83	0.83
7-Jun-04	0.92	0.96	0.97	0.82	0.94	0.94	0.94	1.00	0.96	0.95	0.95	0.92	0.90	0.85	0.82	0.83
11-Jun-04	0.92	0.93	0.95	0.75	0.90	0.94	0.96	0.96	1.00	0.98	0.98	0.95	0.96	0.85	0.83	0.83
18-Jun-04	0.90	0.90	0.94	0.76	0.90	0.93	0.96	0.95	0.98	1.00	0.98	0.98	0.93	0.87	0.84	0.86
25-Jun-04	0.94	0.92	0.96	0.73	0.91	0.93	0.95	0.95	0.98	0.98	1.00	0.95	0.94	0.87	0.84	0.86
2-Jul-04	0.90	0.93	0.95	0.79	0.90	0.97	0.96	0.92	0.96	0.95	0.96	1.00	0.96	0.88	0.87	0.87
8-Jul-04	0.93	0.90	0.94	0.74	0.90	0.90	0.94	0.90	0.93	0.94	0.95	0.94	1.00	0.93	0.91	0.88
23-Jul-04	0.85	0.84	0.86	0.74	0.85	0.84	0.86	0.85	0.87	0.87	0.88	0.91	0.93	1.00	0.98	0.96
30-Jul-04	0.86	0.83	0.86	0.74	0.84	0.83	0.83	0.82	0.84	0.84	0.87	0.91	0.91	0.98	1.00	0.96
6-Aug-04	0.89	0.82	0.86	0.72	0.84	0.80	0.83	0.83	0.86	0.86	0.87	0.88	0.93	0.96	0.96	1.00

Stone Hill 2004 400 mm

Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.96		0.96	0.95		0.95	0.89	0.90	0.90	0.90	0.88	0.92	0.91	0.89	0.93
15-Apr-04	0.96	1.00		0.98	0.91	0.97	0.99	0.95	0.95		0.90	0.91	0.96	0.95	0.93	0.96
23-Apr-04	0.96	0.98		1.00	0.89	0.97	0.99	0.93	0.93	0.92	0.91	0.89	0.94	0.93	0.90	0.95
6-May-04	0.95	0.91	0.89	0.89	1.00	0.93	0.88	0.88	0.90	0.89	0.93	0.89	0.90	0.89	0.90	0.90
10-May-04	0.96	0.97	0.97	0.97	1.00	1.00	0.97	0.93	0.96	0.94	0.93	0.92	0.96	0.95	0.94	0.97
14-May-04	0.95	0.99	0.99	0.99	0.88	0.97	1.00	0.92	0.92	0.92	0.88	0.88	0.93	0.93	0.90	0.95
21-May-04	0.95	0.99	0.97	0.97	0.90	0.97	0.99	0.95	0.95	0.96	0.91	0.93	0.96	0.96	0.94	0.97
7-Jun-04	0.89	0.95	0.93	0.93	0.88	0.93	0.92	1.00	0.99	0.97	0.94	0.96	0.96	0.95	0.93	0.95
11-Jun-04	0.90	0.95	0.93	0.93	0.90	0.94	0.92	0.99	1.00	0.99	0.96	0.98	0.98	0.97	0.96	0.97
18-Jun-04	0.90	0.94		0.92	0.89	0.94	0.92	0.97	0.99		0.96	0.99	0.99	0.99	0.98	0.98
25-Jun-04	0.90	0.90	0.91	0.91	0.93	0.93	0.88	0.94	0.96	0.96	1.00	0.98	0.97	0.95	0.95	0.96
2-Jul-04	0.88	0.91	0.89	0.89	0.89	0.92	0.88	0.96	0.98	0.99	0.98	1.00	0.98	0.98	0.98	0.97
8-Jul-04	0.92	0.96	0.94	0.94	0.90	0.96	0.93	0.96	0.98	0.99	0.99	0.97	1.00	1.00	0.99	0.99
23-Jul-04	0.91	0.95	0.93	0.93	0.89	0.95	0.93	0.95	0.97	0.99	0.99	0.98	1.00	1.00	0.99	0.99
30-Jul-04	0.89	0.93	0.90	0.90	0.90	0.94	0.90	0.93	0.96	0.98	0.95	0.98	0.99	0.99	1.00	0.98
6-Aug-04	0.93	0.96		0.95	0.90	0.97	0.95	0.95	0.97	0.98	0.96	0.97	0.99	0.99	0.98	1.00

Stone Hill 2004 600 mm

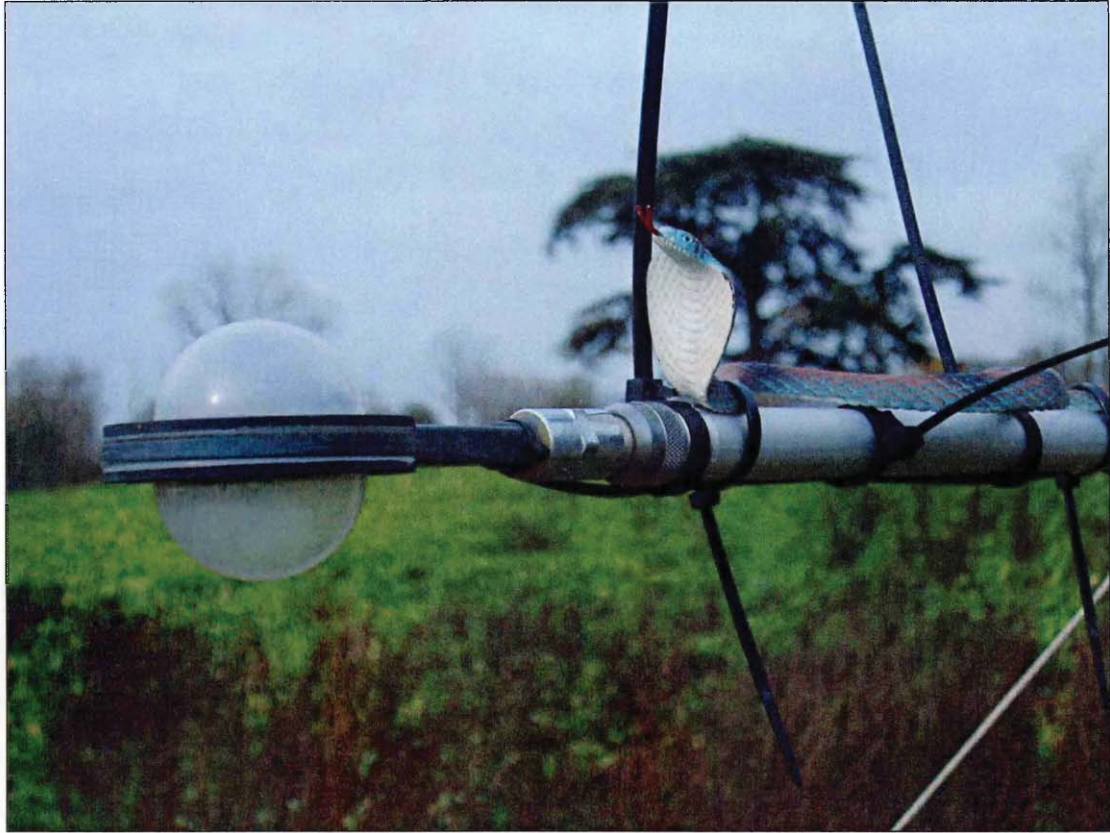
Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.99	0.99	0.98	0.90	0.98	0.99	0.96	0.96	0.96	0.98	0.97	0.97	0.98	0.98	0.98
15-Apr-04	0.99	1.00	0.99	0.99	0.91	1.00	0.99	0.97	0.97	1.00	0.98	0.98	0.99	0.98	0.99	0.98
23-Apr-04	0.98	0.99	1.00	0.91	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.99	0.98	0.99
6-May-04	0.90	0.91	0.91	1.00	0.91	0.89	0.92	0.95	0.94	0.93	0.92	0.92	0.91	0.90	0.93	0.88
10-May-04	0.98	1.00	0.99	0.91	1.00	0.98	0.99	0.97	0.97	1.00	0.98	0.98	0.99	0.98	0.99	0.98
14-May-04	0.99	0.99	0.99	0.89	0.89	0.98	1.00	0.97	0.97	0.98	0.97	0.98	0.97	0.99	0.98	0.99
21-May-04	0.98	0.99	1.00	0.92	0.99	0.99	0.99	0.99	0.99	0.99	0.97	0.97	0.97	0.99	0.98	0.98
7-Jun-04	0.96	0.97	0.99	0.95	0.97	0.97	0.97	1.00	0.98	0.98	0.97	0.96	0.97	0.97	0.98	0.96
11-Jun-04	0.96	0.97	0.98	0.94	0.97	0.97	0.97	0.98	1.00	0.98	0.96	0.97	0.95	0.98	0.97	0.97
18-Jun-04	0.98	1.00	0.99	0.93	0.93	1.00	0.98	0.98	0.98	1.00	0.99	0.99	0.99	0.98	0.99	0.98
25-Jun-04	0.98	0.98	0.98	0.92	0.98	0.97	0.97	0.97	0.96	0.99	1.00	0.99	0.98	0.97	0.98	0.96
2-Jul-04	0.97	0.98	0.98	0.92	0.98	0.98	0.98	0.96	0.97	0.99	0.99	1.00	0.97	0.97	0.97	0.97
8-Jul-04	0.97	0.99	0.98	0.91	0.99	0.97	0.97	0.97	0.97	0.95	0.98	0.97	1.00	0.97	0.99	0.97
23-Jul-04	0.98	0.98	0.99	0.90	0.98	0.98	0.99	0.97	0.98	0.98	0.97	0.97	0.97	1.00	0.98	0.99
30-Jul-04	0.98	0.99	0.98	0.93	0.93	0.99	0.98	0.98	0.98	0.99	0.98	0.97	0.99	0.98	1.00	0.97
6-Aug-04	0.98	0.98	0.99	0.88	0.88	0.98	0.99	0.96	0.97	0.98	0.96	0.97	0.97	0.99	0.97	1.00

Stone Hill 2004 1 m

Variable	8-Apr-04	15-Apr-04	23-Apr-04	6-May-04	10-May-04	14-May-04	21-May-04	7-Jun-04	11-Jun-04	18-Jun-04	25-Jun-04	2-Jul-04	8-Jul-04	23-Jul-04	30-Jul-04	6-Aug-04
8-Apr-04	1.00	0.98		0.92	0.97	0.95	0.96	0.96	0.97	0.95	0.97	0.89	0.90	0.94	0.91	0.91
15-Apr-04	0.98	1.00		0.99	0.96	0.96	0.97	0.99	0.98	0.98	0.98	0.98	0.94	0.95	0.95	0.95
23-Apr-04	0.98	0.99	1.00	0.89	0.96	0.95	0.96	0.99	0.99	0.98	0.98	0.98	0.94	0.95	0.94	0.94
6-May-04	0.92	0.90	0.89	1.00	0.88	0.86	0.89	0.91	0.89	0.88	0.88	0.85	0.86	0.90	0.87	0.88
10-May-04	0.97	0.96	0.96	0.88	1.00	0.97	0.97	0.97	0.98	0.95	0.95	0.91	0.92	0.93	0.93	0.93
14-May-04	0.95	0.96	0.95	0.86	0.97	1.00	0.98	0.98	0.98	0.95	0.96	0.93	0.91	0.93	0.92	0.94
21-May-04	0.96	0.97	0.96	0.89	0.97	0.98	1.00	0.98	0.98	0.96	0.95	0.92	0.92	0.92	0.92	0.92
7-Jun-04	0.96	0.99	0.99	0.91	0.97	0.96	0.98	1.00	0.99	0.96	0.96	0.91	0.92	0.91	0.91	0.92
11-Jun-04	0.97	0.98	0.99	0.89	0.98	0.98	0.98	0.99	1.00	0.97	0.96	0.93	0.92	0.93	0.92	0.93
18-Jun-04	0.95	0.98	0.98	0.88	0.95	0.95	0.96	0.96	0.97	1.00	0.98	0.97	0.97	0.98	0.97	0.97
25-Jun-04	0.97	0.98	0.98	0.88	0.95	0.96	0.95	0.96	0.96	0.98	1.00	0.96	0.96	0.97	0.97	0.98
2-Jul-04	0.89	0.94	0.94	0.85	0.91	0.93	0.92	0.91	0.93	0.97	0.96	1.00	0.97	0.96	0.97	0.97
8-Jul-04	0.90	0.95	0.94	0.86	0.92	0.91	0.92	0.92	0.92	0.97	0.96	0.96	1.00	0.99	1.00	0.99
23-Jul-04	0.94	0.95	0.95	0.90	0.93	0.93	0.92	0.91	0.93	0.98	0.97	0.96	0.99	1.00	1.00	0.99
30-Jul-04	0.91	0.95	0.94	0.87	0.93	0.92	0.92	0.91	0.92	0.97	0.97	0.97	1.00	1.00	1.00	1.00
6-Aug-04	0.91	0.95	0.94	0.88	0.93	0.94	0.92	0.92	0.93	0.97	0.98	0.97	0.99	0.99	1.00	1.00

Appendix VI

How to stop birds attacking Net Radiometers?



Add a plastic snake....It really works!