INSTITUTE of
HYDROLOGY

APPLICATION OF THE MUST
MODEL TO A LOCATION IN
THE OXFORD FLOODPLAIN

A report of a 3month
practical period at the
Institute of Hydrology,
Wallingford, England

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ABSTRACT

This report presents the determination of the inputdata of the MUST-model in order to run it for the Oxford floodplain.MUST is a model for unsaturated flow above a shallow watertable, developed by de Laat(1985) and uses a pseudo steady state approach. Because of the possible gravelextraction at Worton Rectory Farm (Oxon) it is expected that the groundwaterlevel will lower. Adjacent to the gravelextraction are two sites of special scientific interest. For a location in one of these, namely Pixey Mead, the MUST-model is runned for a period from 30th April until 28th October 1986.
The region consists of alluvium and river terrace deposits overlaying Oxford clay.
The requisite meteorological data were all available. The waterlevels have pretty regulary been measured and were checked with tensiometer-observations.
Missing of soil-physical measurements forces to use moisturecontents of comparable soils. The hydraulic conductivities for different matric pressures and for different profileleyers are calculated with the help of a model developed by T.J.Marshall(1985). The resulting hydraulic conductivities are higher than expected. The used heading is grass with a rootingdepth of 30 cm.
Even in September and October 1985, the actual evaporation equals the potential evaporation. This means that the roots can still get enough water. However,summer 1985 was extremely wet and so not very representative.
A lowering of the watertable with 20 cm increases the saturationdeficit in the unsaturated zone with more than 70%,but does not affect the evaporation. The latter is also the case when the rooting depth is shortened from 30 cm to 20 cm.
Varying the hysteretic factor between 0.5 and 2.0 gives exactly the same outputresults.
The MUST-model is not sufficiently tested with respect to hydraulic conductivity during this project in order to conclude something about its sensitivity for this parameter.

ACKNOWLEDGEMENTS

Though all the details of the MUST-model are not understood yet, I've learned quite a lot about the working of this model and about the hydrological situation of the Oxford floodplain .

A practical period of three months is a bit too short for this. When I really started to get the results of 2 months reading, studying and gathering of input data, it was time to leave England and so the Institute of Hydrology.

It was a pity that I could not use the real measured soil physical data. I should like to know the results of these runs. Maybe someone else who is going to continue the 'MUST project' can tell me sometime.

I am very grateful to C.M.K. Gardner PhD for her support and advice, especially in the field of soil physics.

Thankyou C.E. Reeve PhdD for the general support and help on the computer.

I like to thank the Director of the Institute of Hydrology who made my practical period at the Institute possible.

I am grateful to the following as well:

R.B. Bradford BSc, for his general support

J.P. Bell BSc and J.D.Cooper BSc for their soil physical advice.

Miss B.J. Ridler, for the indispensable assistance she rendered.

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SPEND OF TIME

14thOct 1985-27thOct1985:
- reading and studying about the hydrological situation of the Oxfordfloodplain
- introduction to theG.E.C.-computer, learning the commands and writing of some simple Fortan programs for exercise
- general fieldtrip to get an idea about the study-area

28thOct 1985-8thNov1985:
- studying the manual of the MUST-model
- studying and trying to understand the proper program
- running of the program for three example situations, given in the MUST-manual
- making an interimreport

10thNov 1985-22thNov1985:
- fieldwork during two days to get cores of some boreholes in the Oxfordfloodplain
- looking at the cores, distinguishment of the different layers, estimation of rootingdepth, colour, porosity and structure
- one day to Cambridge for measurements of airpressure and some meteorological observations (concerns different project)

25thNov1985-6thDec1985:
- calculation of the mean weekly meteorological data
- interpolation and extrapolation of the measured watertables
- calculation of the waterlevels with the help of tensiometer observations and checking with directly measured watertable

8thDec 1985-20thDec 1985:
- drawing the PF-curves(using the soilwatercontents of Soil Survey Soils comparables with the Oxfordfloodplain soillayers)
- changing a few things in the Marshall subroutine (including making a mainprogram of it for the G.E.C.-computer)
- running the program for a location in the Oxford floodplain

-visit to the Institute of Hydrology in Plynlimon, Wales and its research-area; this project is about the hydrological-chemical situation of the river Wye and Severn in connection with afforestation (3 days)

23thDec 1985-3thJan 1986-running of the model with different hydrological and soilphysical data; testing of the sensitivity of the MUST-model with respect to changes in certain parameters

6thJan 1986-17thJan1986:-preparations for a seminar

-seminar and discussions

29thJan1986-14thFeb1986:-back in the Netherlands:continuing writing report

INTRODUCTION

Because of the possible gravel extraction at Worton Rectory Farm (Oxon), it is expected that the groundwater level will lower. Adjacent to the gravel extraction are two sites of special scientific interest (S.S.S.I.): Pixey Mead and Yarnton Mead. See figures 1 and 2 for the location. Shallow confined groundwater levels may be of significance to the protection of plant communities here.

In 1983, the Institute of Hydrology Wallingford started a study in order to find out how any gravel workings might proceed without detriment to the S.S.S.I's. It was the intention to predict the consequences of engineering works in advance of any gravel extraction. During a hydrogeological program in January/February 1984 it was illustrated that, when high groundwater levels existed, the head control on the groundwater system was the river Thames. (More about the geohydrological situation is told in chapter 2). It was also shown that the volumes of groundwater flow were very small relative to the surface water flow. There was reason to believe that these conditions will prevail during low groundwater conditions (caused by gravel extraction). These results allowed to conclude that during gravel extraction it will be possible to control the groundwater levels in the mead by using appropriate land drainage schemes.

Predictive studies either for water control during gravel working or for establishing after use alternatives must involve modelling. Modelling was the only realistic way of investigating engineering solutions in advance and thus reducing the risks of severe and unexpected environmental change. (Institute of Hydrology, 1984).

Calibration of the model and its use in operational predictions for the Worton Rectory site would form a major element of the project.

It turned out that the model MUST was very useful. This is a simulation model for unsaturated flow above a shallow water table.

MUST differs from many other models in that it does not simulate unsaturated flow in great detail. The time steps are in the order of magnitude of days and the exact soil moisture distribution is not calculated. This less detailed approach is in general acceptable in view of the accuracy of available soil physical data and the horizontal heterogeneity in the field. As a result,MUST uses little computer time and allows simple data management for its execution. See chapter 3 for the theory. Initially it was the intention to run the program for at least three different sites:

one site, where the groundwater level is always in the alluvium (PX11)
one site where the groundwater level is always in the gravel (UFS27)
one site where the groundwater level is sometimes in the alluvium, sometimes in the gravel (WR15 and maybe WR8).

See figure 2 for the locations of these boreholes. The watertables need to be specified in the model. However, the watertables for UFS27, WR15 and WR8 had rarely been measured.

This was one of the reasons to run the model only for PX11.

For the meteorological data and groundwater tables see chapter 5.

The soil moisture contents and hydraulic conductivities for matric pressures in a range of 0 to 16000mbar are necessary. These values, especially for the high matric pressures were not available by the time the model could be run.

Therefore, data of some comparable soils (Soil Survey data) were used to get the soil moisture contents for PX11. The hydraulic conductivities were calculated with the help of a program based on Marshall's equation. (Marshall, 1958). In chapter 4 are more details about this.

In chapter 6 is told about the results of the runs. An important point is if the roots can still get enough water when the groundwater level is lowered (because of gravel extraction).

The sensitivity of the MUST-model is tested for hysteretic factor, rooting depth, heterogeneity, groundwater level and hydraulic conductivity in combination with soil moisture content.

Finally chapter 7 contains the conclusions and chapter 8 some suggestions for further research.

Fig 1. Location of research area in Gr. Britain (in red)

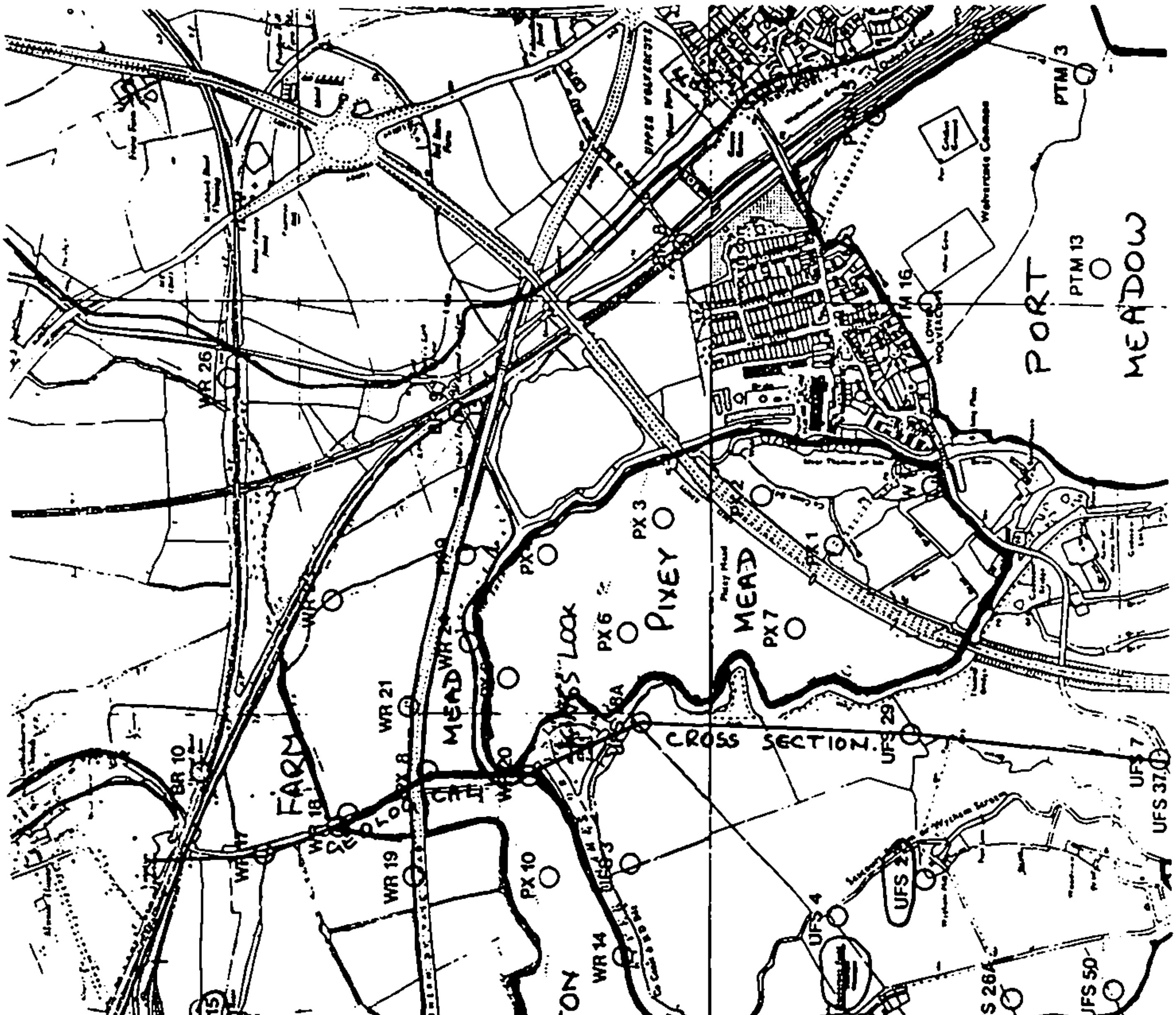


Fig 2. Location of the Sites of Special Scientific Interest and the boreholes

2 GEOLOGY AND GEOHYDROLOGY OF THE OXFORD FLOODPLAIN

2.1 Geology

2.1.1. Introduction

Most of the region within and around the study area is dominated by the Thames Valley with its Quaternary alluvium and river terrace deposits overlaying Mezozoic Oxford Clay (see figure 3).

The alluvial aquifer which bordering the Thames in this region comprises First or Floodplain Terrace with small areas of second or Summertown - Radley Terrace where these patches are in hydraulic continuity. Generally speaking the aquifer can be considered as consisting of relatively thin, fluvial sands and gravels sandwiched between bedrock clay and overlying alluvial mud.

2.1.2 Alluvium

Most of the Thames floodplain is mapped as alluvium. A notable exception occurs on Port Meadow. Elsewhere thicknesses of up to 4 metres occur. The alluvium is a soft mud, often with much shelly and organic material with occasional discrete peat horizons towards the base. It is hoped that such organic horizons will enable reconstruction of the ecological history of the floodplain environment.

Particle size analysis showed alluvium at UFS18 (see figure 2) to be 65% clay and 35% silt where as alluvium exposed at a river bank section of Seacourt Stream showed 40% clay and 60% silt. It is postulated that the alluvium represents over bank flood deposits, the product of soil erosion caused by early defforestation.

Areas of thick alluvium have been proved to underlie Pixey Mead and the northern part of Worton Rectory Farm. An explanation for the varying thicknesses of the alluvium is a 'channel' system some-what different to the present floodplain topography, accounting for areas of thick alluvium.

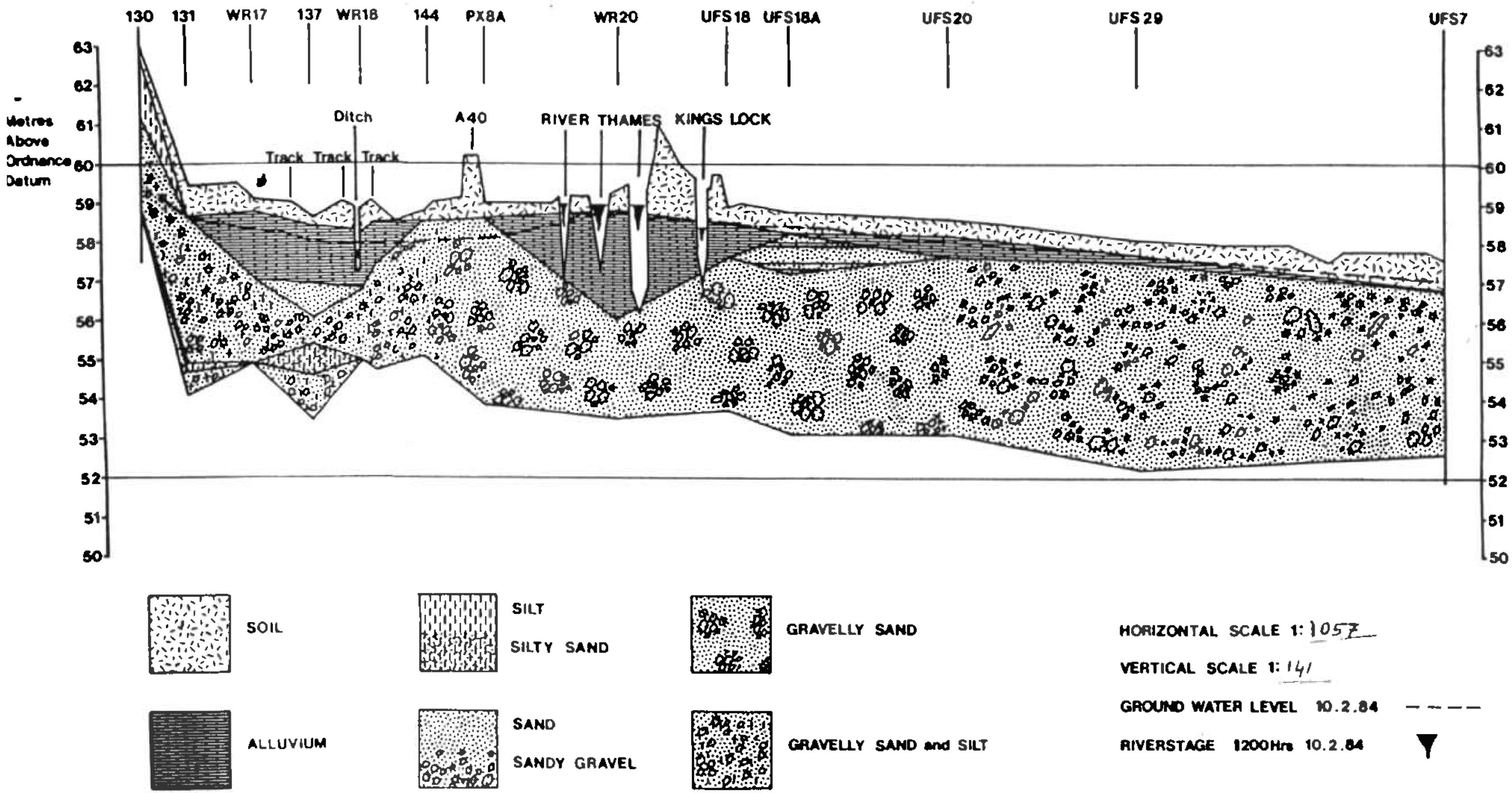


Fig 3. GEOLOGICAL CROSS SECTION OF THE OXFORD FLOODPLAIN

2.1.3 Sand and gravel

Sand and gravel thickness approximates aquifer thickness because most of the aquifer is confined. Thicknesses of over 5 m are present in the mid flood plain areas between alluvium filled channels. Generally the thicker of the alluvium covering, the thinner the underlying gravel.

The sands and gravels are largely composed of fine to coarse, rounded to subrounded limestone pebbles. Fines content decreases from valley sides to the middle of the floodplain. The valley sides are dominated by gravelly sand with silt, whereas clean gravelly sand and sandy gravel occur in the central parts of the floodplain.

The gravel was deposited in a cold environment (Upper Pleistocene) by a river regime (arctic proglacial analogue). For the thickness of the gravel see figure 4.

2.2 Geohydrology

2.2.1 Groundwater conditions

Broadly the Thames between Magley Pool and Kings Lock divides the area into two quite distinct zones. Downstream of Kings Lock groundwater movement is approximately from north to south. North of the Thames at Kings Loch groundwater flow is quite different and unexpected. The surface of the groundwater body is saucer shaped with radial flow inward.

The shallowest depth to groundwater is less than 0.5 m.

Within the area of Worton Rectory Farm water levels were up to 1.8 m below surface reflecting the depressed water table around a drainage ditch. (during observations January and February 1984).

2.2.2 Relationships with surface water

Across the area the groundwater level stands variously within either the gravels, the alluvium or the soil layers. Generally we have to assume that the alluvium is either of very low permeability or is impermeable and therefore in places the aquifer is essentially confined. Yarnton Mead and Pixey Mead are areas of confined aquifers. During observations at 10 of

February 1984, Yarnton Mead had a smaller head (0-1 m) than Pixey Mead (1.0 m - 2.5 m). Shallow confined groundwater levels may be of significance to the protection of plant communities.

Potentially the zones where river stage is above groundwater level, surface water can enter the groundwater system providing that permeable beds also occur. The main system of the Thames and the Oxford Canal are potential leakage sites (influent).

Minor water courses appear to have water levels below groundwater level. They are effluent and capable of receiving inflow from groundwater again providing that a hydraulic connection exists.

The very dynamic nature of the groundwater body, the rapid changes from confied to unconfined conditions and the importance of the whole surface water network do not make groundwater modelling easier.

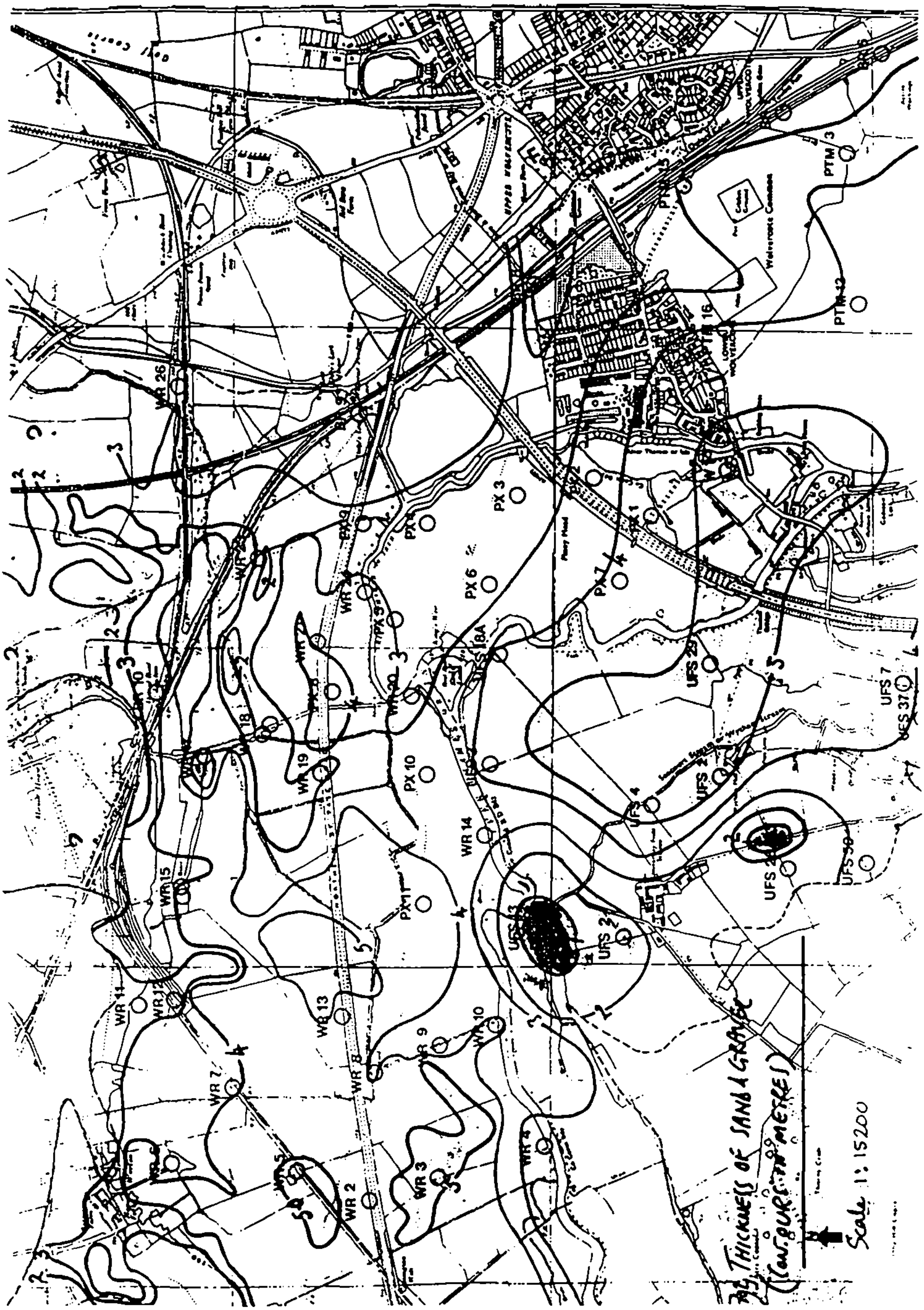


Fig. Thickness of Sand & Gravel (Contours in metres)

Scale 1:15200

3. THEORY AND REQUISITE DATA OF THE MUST-MODEL

3.1 Summary of the theory of the MUST-model

3.1.1. Introduction

MUST is a simulation model for unsaturated flow above a shallow water table. In the next paragraphs (concerning the theory of the model) is explained:

- the pseudo - steady state approach including the way the model is based on the "Law of Darcy", the calculation of the saturation deficit curves and the use of these.

the lower and upper boundary solution.

3.1.2 Pseudo steady-state approach

MUST simulates transient flow by a succession of steady-state situations. Only one dimensional vertical flow is considered because flow in the unsaturated zone is predominantly in the vertical direction. The equation for steady vertical flow may be written in the following way (Law of Darcy):

$$\bar{q} = K(p) \left(\frac{1}{\rho g} \frac{dp}{dz} + 1\right) \qquad (1)$$

with	$\bar{q}$	=	steady vertical unsaturated flow	(cm/d)
	K	=	hydraulic conductivity	(cm/d)
	ρ	=	density of water (ρ=1000)	(kg/m^3)
	g	=	acceleration due to gravity (g=g.δ)	(m/s^2)
	p	=	matric pressure (negative) relative to atmospheric pressure	(Pa;mbar)
	z	=	height above reference level	(cm;m)

The steady flux $\bar{q}$ is taken positive upwards.

Separating the variables and solving for z gives

$$z = \frac{1}{\rho g} \int_{o}^{p} \frac{k(p)}{\bar{q} + K(p)} dp \qquad (2)$$

where the reference level of z is chosen at the phreatic level, at which level z=o and p=o. The relation between p and z for a particular steady flux $\bar{q}$ is termed pressure profile ($z(\rho\bar{q})$). Given the relation between moisture content and matric pressure $\theta(p)$ known as PF-curve, pressure profiles are easily transferred into moisture profiles $z(\theta,q)$.

The schematization of the flow system is shown in Fig.5.

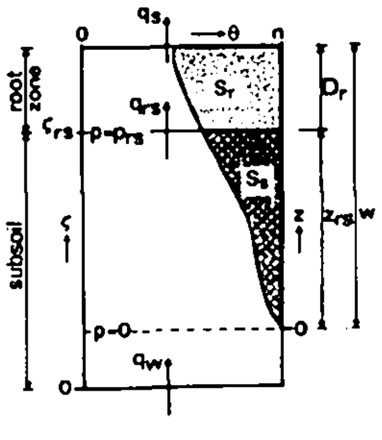


Fig. 5 Schematic presentation of the unsaturated flow system.

The lower boundary of the unsaturated zone is chosen as a fixed level below the lowest water table depth. The vertical co-ordinate direction ζ equals zero at the lower boundary and is taken as positive in upward direction.

The system is divided in two main layers:

- the rootzone in which most of the roots are present
- the subsoil, the zone below the rootzone until the lower boundary.

The depth of the rootzone is constant and equals D_r while the interface between the rootzone and the subsoil is at a height ζ_{rs}. The flux across the interface between the rootzone and the subsoil is denoted q_{rs} and the flux across the upper boundary and lower boundary by q_s and q_w, respectively. All fluxes are taken to be positive upwards.

For a steady flow situation the soil moisture distribution in the subsoil corresponds to the moisture profile $z(\theta,\bar{q})$ for the appropriate steady flux $\bar{q}$. The phreatic level (z=o) changes with time, depending on the value for z_{rs}, the distance between the lower side of the rootzone and and the water table.

The saturation deficit of the subsoil S_s is calculated by intergrating the pore space in the subsoil not filled with water. Systematic integration of moisture profiles for many values of z_{rs} yields for each steady flow situation $\bar{q}$ a relation between S_s ad z_{rs} which relations together from the saturation deficit curves for the subsoils S_s $(z_{rs},\bar{q})$.

The depth of the water table below soil surface is W. At the phreatic level p=o and at the height $\zeta=\zeta_{rs}$ the matric pressure is denoted by p_{rs}.

As flow in the rootzone is largely governed by the water uptake of roots, the gradient of the hydraulic potential in the rootzone is assumed equal to zero. It is supposed that the water extraction by the crop is such that the soil moisture distribution in the rootzone approximates an equilibrium situation at all times. Consequently $dp = -\rho g dz$. So for a given matric pressure at the interface rootzone - subsoil (p_{rs}), the soil moisture distribution is known. This is because you know the density of water (ρ), the acceleration due to gravity (g) and dz, and the relation between moisture content and matric pressure is given.

The saturation deficit in the rootzone is found by integrating that pore space not filled with water. Systematic integration for a number of matric pressure values at the interface root-zone subsoil yields the saturation deficit curves for the rootzone $S_r(p_{rs})$.

The saturation deficit of the entire unsaturated zone is the amount of water needed to completely saturate the soil and equals the volume of air present between the lower boundary and the soil surface.

$$S_u(p_{rs}, \bar{q}) = S_r(p_{rs}) + S_s(p_{rs}, \bar{q}) \tag{3}$$

with

S_u	=	saturation deficit entire unsaturated zone	(cm)
S_r	=	saturation deficit root zone	(cm)
S_s	=	saturation deficit subsoil	(cm)
p_{rs}	=	matric pressure at interface root-zone subsoil	(mbar)
$\bar{q}$	=	steady vertical unsaturated flow	(cm/d)

3.1.3. Upper and lower boundary solution

In Appendix A is shown that the steady state situation is fully determined by only two parameters (e.g. the saturation deficit of the rootzone S_r and the steady flux in the subsoil $\bar{q}$). The use of saturation deficits reduces the solution of the steadystate situation to a problem of two relations with two unknowns (S_r and $\bar{q}$). The steady-state solution corresponding to the upper boundary flux of the subsoil is termed upper boundary solution.

If the rootzone desiccates to wilting point the calculation procedure yields furthermore the actual flux across the soil surface. When there is a large downward flux across the lower boundary, the upper boundary solution is unsuitable for computing the water table depth. For a downward lower boundary flux condition the position of the phreatic level is therefore simulated by a pseudo steady-state approach to percolation applying to the lower part of the unsaturated zone. The steady-state solution corresponding to the lower flux of the subsoil is termed upper boundary solution. The upper and lower boundary solution are combined into one simulation model.

The model for the lower boundary solution does not consider flow in the upper part of the subsoil. The initial moisture profile serves as the upper boundary of the model. When the situation is followed by a time, increment during which q_w the flux across the lower boundary is negative, superposition of the moisture profile for this $\bar{q}$ on the initial curve yields the soil moisture distribution. Appendix A shows how you can find the saturation deficit of the percolation profiles.

The percolation profile disappears when q_w becomes positive or when the phreatic level calculated with the lower boundary solution is above the level found with the upper boundary solution. The latter situation is likely to occur after a period of prolonged rainfall excess in the presence of a shallow water table.

A flow chart of MUST is given in Appendix B.

3.2 Requisite input data for the MUST-model

The requisite input data for the MUST-model are distinguished in:

- General input data
- Soil physical input data
- Meteorological input data
- Hydrological input data (water tables)

Prior to the simulation of unsaturated flow saturation deficit curves have to be calculated by the model. For each steady flow situation $\bar{q}$ the saturation deficit for the subsoil S_s is computed for a standard series

S_s and p_{rs} is carried out for a standard series of 18 steady flow situations $\bar{q}$. See for both standard series Appendix C. To improve interpolation results, values for the standard series have been selected at irregular intervals.

The general inputdata include the length of the time increment. If the transpiration is to be computed by the model the number of the day in the year at the start of the simulation and the year itself have to be specified. For more details see chapter about the general inputdata.

Concerning soil physical data the soil water contents and the hydraulic conductivities for the different layers of the soil for the different standard series of matric pressures and steady flow situations have to be specified. The rooting depth is necessary as well.

The meteorological input data contain the observed wind velocity, the fractional duration of sunshine, the fractional relative humidity, the air temperature and the precipitation. These data are used to calculate the actual evapotranspiration. The actual evapotranspiration includes the evapotranspiration flux of intercepted water, the actual transpiration and the actual soil evapotranspiration. This calculation is based on the PENMAN - formula of Monteith and Rijtema. See Appendix D.

The water tables need to be specified for every timestep (or instead of this:- the lower boundary flux is specified or the function of the watertable depth - lower boundary flux).

4. GENERAL INPUTDATA

4.1 Introduction

Initially it was the intention to run the MUST model for at least 3 different sites:

> PX 11 , where the groundwater level is permanently in the alluvium
> UFS 27, where the groundwater level is permanently in the gravel
> WR 15 (and maybe WR 8), where the groundwater level is sometimes in the gravel, sometimes in the alluvium.

See figure 6 (for the location of those sites). Because a lot of input data were not available yet and there was not enough time left, the MUST model was only run for PX 11. Still some measurements and calculations were done for all four sites.

4.2. Choice of time increment

The time that it takes before an approximate steady flow situation is reached after a change in the upper boundary flux condition depends on the rate of change, the initial soil moisture distribution, the water table depth and the soil physical properties. With shallow water tables this time varies from less than one hour for coarse sand to more than 10 days for loamy soils. At PX 11, there is a top layer of loam of 20 cm: sand/gravel starts at 96 cm below soil surface. See chapter 5 For many flow situations an approximate steady state may be reached within one day, which is one of the reasons why time steps for simulation with MUST should preferably be taken at one day intervals.

However, the purpose is to simulate a period of half a year. The choice of a timestep between 5 and 10 days is then more attractive. Timesteps of a week were chosen. This rather big timestep results in averaging the effect of a single wet day in an otherwise dry period.

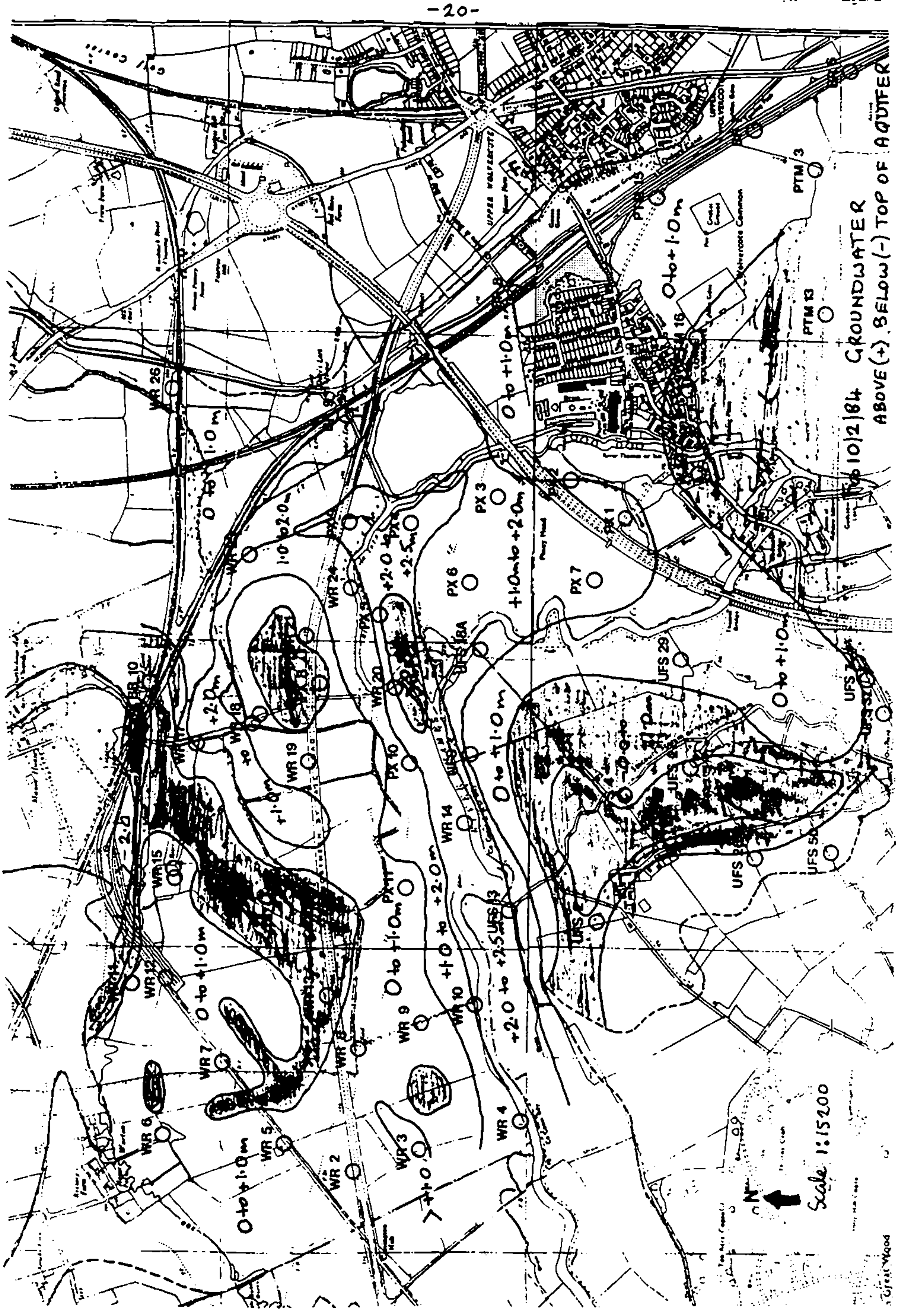
The effect of the length of the time step on the simulated potential evapotranspiration of the chosen crop is two-fold. A large potential evapotranspiration rate may result in a leaf water pressure p_l which is smaller than the critical value p_1 due to which the canopy resistance starts to increase (Appendix D). This leads to smaller potential evapotranspiration rates. Since extreme weather conditions are reduced for larger timesteps the reduction in potential evapotranspiration will occur less frequently and to a smaller degree. Hence, a larger time increment results in larger values for the potential evapotranspiration.

The other effect is due to the introduction of interception. A larger time step reduces the frequence of rain storms and consequently the amount of water intercepted by the vegetation. In order to obtain the same evapotranspiration from the interception reservoir for larger time steps, the size of the interception reservoir has been increased. This has been done with the help of correction factors which inlude both effects, as discussed above.

4.3 Start of Simulation

Since the evaporation is computed by the model, the number of the days in the year at the start of the simulation and the year itself were specified. The former is necessary for the computation of crop height, soil cover and solar radiation, the latter for the identification of leap years. Simulation for PX 11 was started 30 April 1985. So the first timestep (of 7 days) is: 30 April 1985 - 6 May 1985. The simulation was finished 20 October 1985. (Last time-step is 22 - 28 October 1985). Latter date was the latest day of which meteorological data were already available by the time the running could by started.

The whole simulation period is about 6 months but can very easily be changed in a longer period. 6 months corresponds with 26 time-steps.


10/2/84 GROUNDWATER
ABOVE (+) BELOW (-) TOP OF AQUIFER
Scale 1:15200
N
0 to +1.0m
+1.0m to +2.0m
+2.0 to +2.5m
+1.0 to +2.0m
0 to +1.0m
+2.0 to +2.5m
-2.0
+2.0m
PX 3
PX 6
PX 7
PX 1
PX 10
PX 11
WR 2
WR 3
WR 4
WR 5
WR 6
WR 7
WR 9
WR 10
WR 12
WR 14
WR 15
WR 19
WR 20
WR 24
WR 26
UFS 13
UFS 18A
UFS 29
UFS 5A
PTM 3
PTM 13
BR 10

5. SOIL PHYSICAL INPUTDATA

5.1 General

The MUST-model needs the soilwatercontents and the hydraulic conductivities of the different layers for the different standard matric pressures (see appendix C).
The rootingdepth, landuse and hysteretic factor haveto be specified.

5.2 Differences between different layers, landuse and rootingdepth

The different layers were distinguished for four different sites (6thNovember 1985).

- borehole 0153 corresponds with PX11
- borehole 0253 corresponds with WR8
- borehole 0353 corresponds with WR15
- borehole 0453 corresponds with CFS27

The pictures of the profiles are in appendix E. The colour, structure, porosity, abundancy of roots and stones were determined with the help of the Soil Survey Fieldhandbook.
Borehole 0453 was only until a depth of 74 cm below soilsurface because the gravel started here.
The first part of the core was from 0-50 cms below soilsurface for all four sites. The second part of the core started at 50 cm and finished at 96 cm below soil surface (apart from 0453:74 cm).
Unlike 0153 and 0253, the other two boreholes were dry during the observations. It was rather difficult to feel what kind of soil it was for 0353 and 0453. Therefore these cores were rewetted. The colours of the different layers of latter cores were determined when the cores were dry.

The results are in the following table:

Table 1 Yarnton Profiles (5th November 1985)

horizon		
0153		
0-12 cm,	Moist,	granular structure, abundant roots
A		7.5 YR 2/2 brownish black
loam		
12-15	Moist,	changing colour-diffuse boundary
loam		7.5 YR 3/2 mottled with 7.5 YR 4/4
15-20	Moist,	orange more predominant over brown,
loam		granular structure, abundant roots
20-43	Moist	2.5 YR 5/2 with same orange mottling,
clay		fine subangular blocky structure,
		many roots, 0.5 to 0.1% fine pores
43-79	Wet	2.5 GY 5/1 olive grey mottled with 10 YR 6/8
silty clay		bright yellowish brown olive grey is predominant
79-97		many roots, fine pores 0.1%
		2.5 gy4/1 (bluey clay) with large mottles of
silty clay		10YR 5/8 yellowish brown with intermediate shades,
		common very fine roots, fine pores 0.1%
horizon		
0253		
0-10 cm	Moist	granular structure 10 YR 3/2 brownish black.
A		abundant fine roots and some coarse wood roots
loam		
10-15 cm	Moist	changing colour diffuse boundary, 10 YR 4/2
loam		greyish yellow brown
		abundant fine roots and some coarse woody roots,
		granular structure.
15-51 cm	Moist	fine blocky structure
silty clay/		10 YR 5/3 dull yellowish brown with some orange
clay		mottling 10 YR 6/8 bright yellowish brown, many roots
		0.1 - 0.5% very fine pores.
51-83 cm	Wet	2.5 GY 6/1 olive grey with large mottles of 10 YR 5/8
clay/silt		yellowish brown
(less clay)		few very fine roots, 0.5% very fine pores

83-96 cm clayey silt	Wet	2.5 GY 5/1 olive grey with large mottles 10 YR 6/8 bright yellowish brown few very fine roots, 0.1% very fine pores.

horizon — 5th and 6th November 1985

0353

0-12 cm A loam	Moist	granular structure, 7.5 YR 3/2 brownish black, abundant fine roots, a few little stones
12-20 loam	Moist	changing colour diffuse boundry 7.5 YR 4/2 greyish brown abundant fine roots, few little stones, granular structure
20-36 cm clay/loam	Dry	10YR 7/2 dull yellow orange (predominantly) with a few 10 YR 5/8 bright yellowish brown, fine blo cky structure, common fine roots, 0.5% fine pores. moderately stoney.
36-88 cm	Dry	10 YR 6/4 dull yellow orange, with a few mottling 10YR 5/8 yellowish brown, yellowish brown predominantly, fine blocky structure , 0.5% very fine roots, common stones.
88-96 cms sandy loam	Dry	10 YR 7/1 light grey with large mottles of 10YR 6/8 bright yellowish brown. 0.5% very fine pores Yellowish brown predominantly, few very fine roots, fine blocky structure.

horizon

0453

0-20 cm A loam	Dry	granular structure 7.5 YR 3/2 brownish black, abundant fine roots, a few very small stones
20-62 cm silty loam	Dry	changing colour diffuse boundary 7.5 YR 3/4 dark brown (predominantly) with 7.5 YR 6/6 orange, many to common fine roots granular structure common small stones

62-74 cm	Dry	7.5 YR 3/2 brownish black with 7.5
sandy loam		YR 6/6 orange (predominantly)
		few very fine roots
		0.1 - 0.5% very fine pores
		fine blocky structure
		common small stones

The landuse is grass. Because there was still an abundant amount of roots at a depth of 30cm (for PX11), the rooting depth was fixed at 30 cm. This is the maximum rooting depth of grass (De Laat, 1985). However, there are still a lot of roots below 30 cm. This is probably because the ordinary grass is mixed with other kinds of grass with a deeper rooting depth.

The runs were all done with a heading of grass with a corresponding maximum rooting depth of 30 cms. The depth of the rooting zone is an important parameter, since it determines to a large extent the amount of water that is available for the crop. It indicates to what depth the soil may be dessiccated to wilting point by the roots.

MUST does not allow a varying rooting depth. So this value is constant throughout the simulation period. This approach is in general acceptable as in the beginning of the growing season soil moisture conditions hardly affect evapotranspiration; should this be the case later in the season, the roots are already fully developed.

5.3 Calculation of the soil moisture contents

Initially it was the intention to use the measured soil water contents of 0153 etc for the different standard series of matric pressures. However, November 1985, these measurements started. It takes quite a long time to get the water contents for the high matric pressure values, such as 16.000 mbar. These measurements were not finished by the time the model could be run. Because of that it was decided to run the model only for PX11 and using the data of the Soil Survey of England and Wales. (Shardlow data).

The bulk densities, texture, boundaries between different layers, landuse and the abundancy of stones of 0153 and the Shardlow soils were compared. In this way the top layers of a Fladbury soil and the sand/gravel layer of a Badsey soil turned out to be comparable with the corresponding layers of 0153. See Appendix F.

For the MUST-model the soil moisture contents for 13 matric pressures in the range from 0 to 16000 mbar are necessary but the Soil Survey data contain only the saturated water contents and the soil moisture contents for 50, 100, 900, 2000 and 15000 mbar. These values were interpolated and extrapolated (to 16000 mbar) in order to find the water contents for the standard matric pressures. In figure 7 PF = $^{10}\log p_m$, with p_m = matric pressure in mbar, has been plotted against water content for the different layers of PX11.

5.4 Calculation of the hydraulic conductivities

5.4.1 General

There are different ways to calculate the unsaturated hydraulic conductivities for different matric pressure values. The Marshall equation turned out to be useful. Furthermore, a subroutine was available of this equation. The subroutine calculates the hydraulic conductivity of a porous material from water content vs. suction data by means of a model developed by T.M. Marshall (1985). The equation giving the conductivity is:

$$K = \frac{g}{\eta} \frac{c^2}{h^2} \left(\frac{1}{h_1^2} + \frac{3}{h_2^2} + \dots + \frac{2n-1}{h_n^2} \right) \qquad (4)$$

where h_1, h_2 ... and h_r represent the mean suction in the equal porosity classes: h_1 belongs to the class with the largest pores and h_n belongs to the class with the smallest.

K	=	hydraulic conductivity	(m/s)
c	=	saturated watercontent	
g	=	acceleration due to gravity	(m/s^2)
η	=	viscosity	(Pas)
n	=	amount of pore classes	

The hydraulic conductivity is calculated with successively fewer terms in the equation. This corresponds to the larger pores draining as the moisture content of the material decreases.

5.4.2 Use of the Marshall program for PX11

Values for $1/h^2$ for use in equation 4 can be obtained for each of n classes from the corresponding areas under the cumulative curve for pore space plotted against $1/h^2$. However if n is sufficiently large h_1, h_2 ... h_n are given with little error by the suction corresponding to the mean water content of each class (i.e. the mean suction in each class). The last mentioned method was used, n (the number of the pore classes) was taken as 14, corresponding to a pore class interval c/n.

For the 14 different water contents from saturated water content until c/n (with steps of c/n between successive values) the corresponding PF values were read from the PF-curves for the different layers of PX 11. (See figure 7).

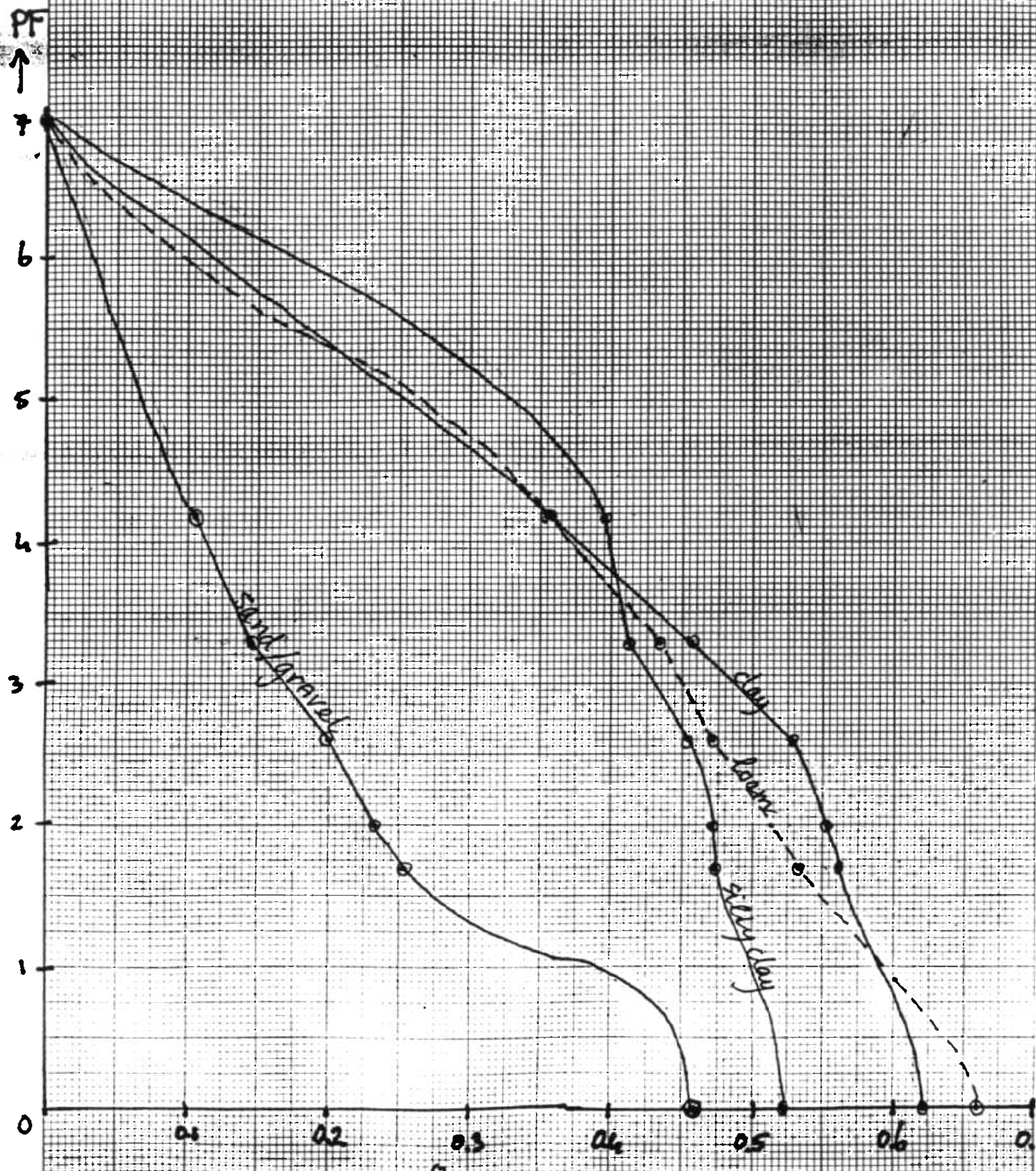


Fig. 7 PF-curves of the different layers of PX11

For the PF-values higher than the values corresponding to 15 bar the PF-curve was extrapolated with he help of the (shapes of) PF-curves of respectively loam, clay, silty clay and sand/gravel of the comparable Dutch soils. (Koorevaar, 1983). In the same way the PF curves were interpolated between the measured values. Consequently the PF-curves for the different layers may be inaccurate.

The resulting mean suction values for the different pore-classes and the saturated soil water contents for the different layers of PX11 were input in the program.

Unlike Marshall who started running his program with the saturated water contents for a mean suction value of 12.80 cm for OSO flaco sand, the Marshall program for PX11 was run as follows:

The suction value for the saturated water content was given an abitrary value. (This is possible because for the higher suction values you don't need the previous suction values to calculate the hydraulic conductivity). So the corresponding hydraulic conductivity is arbitrary as well.

$(\theta - \frac{c}{n})$ as soil moisture content was corresponding to the first mean value of suction. This was done because in reality the saturated water content corresponds to a suction value of 0 cm. It was thought that this was a better way of doing estimation.

For the output of the Marshall program for the sand/gravel layer see Appendix G.

The results were plotted : hydraulic conductivity against water content. The plotted values were interpolated and extrapolated to the saturated water content. Again this extrapolation was guessed and was possibly not very accurate, but as accurate as possible. For the soil water contents corresponding to the suction values needed for the MUST-model the hydraulic conductivity was read from the graph and became input for the MUST-model. See table 2.

Table 2
Soil moisture contents and hydraulic conductivities used for PX11 (calculated with the help of Soil Survey data from Shardlow and the Marshall program)

Loam, Fladbury SP83/4759

matric pressure (mbar)	PF - value	Soil moisture content θ	hydraulic conductivity ln (cm/d)	
0	-00	0.660	0.800	10^{4}
10	1.00	0.593	0.681	10^{3}
20	1.30	0.566	0.162	10^{3}
31	1.49	0.549	0.599	10^{2}
50	1.70	0.533	0.225	10^{2}
100	2.00	0.513	0.619	10^{1}
250	2.40	0.484	0.780	
500	2.70	0.465	0.228	
1000	3.00	0.450	0.837	10^{-1}
2500	3.40	0.427	0.190	10^{-1}
5000	3.70	0.399	0.395	10^{-2}
10000	4.00	0.372	0.192	10^{-3}
16000	4.20	0.350	0.405	10^{-3}

Clay, Fladbury SP 83/4759

matric pressure (mbar)	PF - value	Soil moisture content θ	hydraulic conductivity ln (cm/d)	
0	-00	0.621	0.999	10^{3}
10	1.00	0.585	0.245	10^{3}
20	1.30	0.577	0.147	10^{3}
31	1.49	0.569	0.550	10^{2}
50	1.70	0.561	0.180	10^{2}
100	2.00	0.553	0.800	10^{1}
250	2.40	0.548	0.400	10^{1}
500	2.70	0.522	0.399	
1000	3.00	0.493	0.131	
2500	3.40	0.442	0.108	10^{-1}
5000	3.70	0.408	0.270	10^{-2}
10000	4.00	0.378	0.750	10^{-3}
16000	4.20	0.352	0.280	10^{-3}

Table 2 continued

Silty clay, Fladbury SP83/4759

matric pressure (mbar)	PF - value	soil moisture content θ	hydraulic conductivity ln (cm/d)	
0	-00	0.522	0.490	10^{4}
10	1.00	0.502	0.281	10^{3}
20	1.30	0.495	0.107	10^{3}
31	1.49	0.487	0.351	10^{2}
50	1.70	0.477	0.900	10^{1}
100	2.00	0.472	0.500	10^{1}
250	2.40	0.461	0.800	
500	2.76	0.447	0.108	
1000	3.00	0.437	0.541	10^{-1}
2500	3.40	0.404	0.720	10^{-2}
5000	3.70	0.384	0.160	10^{-2}
10000	4.00	0.360	0.681	10^{-3}
16000	4.20	0.345	0.319	10^{-3}

Sand/gravel, Badsey TF 10/2363

matric pressure (mbar)	PF - value	soil moisture content θ	hydraulic conductivity ln (cm/d)	
0	-00	0.465	0.900	10^{4}
10	1.00	0.362	0.109	10^{4}
20	1.30	0.299	0.101	10^{4}
31	1.49	0.274	0.355	10^{2}
50	1.70	0.254	0.112	10^{2}
100	2.00	0.233	0.321	10^{1}
250	2.40	0.211	0.560	
500	2.70	0.184	0.110	
1000	3.00	0.168	0.380	10^{-1}
2500	3.40	0.134	0.395	10^{-2}
5000	3.70	0.118	0.192	10^{-2}
10000	4.00	0.110	0.151	10^{-2}
16000	4.20	0.105	0.180	10^{-3}

5.4.3 Discussion about Marshall program

In order to apply the equation of Marshall's model, it is necessary to have a reliable measurement of size distribution of pores and since this is usually done by suction methods, the accuracy of these in swelling materials may limit the accuracy of the calculation for soils of moderate or high clay content. The equation has only been tested on data for flow of water through saturated and unsaturated sand. So the results of clayey soils are questionable.

The hydraulic conductivity for the standard matric pressures used for the MUST-model are in table 2. The results were higher than was expected, though compared with some other graphs (of hydraulic conductivities plotted against suction) of comparable soils, the results may be reasonable.

Although Marshall did not use a matching factor, later workers have modified the Marshall calculation to improve prediction ability by using a matching factor. K_s/K_{sc} has been introduced to match the calculated and observed conductivity at saturation. However, the saturated water contents had not been measured when the running started. Therefore the matching factor was omitted.

After the running of the program with the hydraulic conductivities calculated according to Marshall, a paper was found about the results of Marshall's equation (Nielsen, 1960). The conclusion done by Nielsen was that the values obtained by the Marshall method were all considerably higher than the measured values.

It was a pity that the real measurements were not available yet. This made it impossible to compare the "Marshall values" with the measured ones.

5.5 Hysteretic factor

Soil moisture characteristics $\theta(p)$ and hydraulic conductivity relations $K(p)$ are subject to hysteresis. Though the effects may be considerable they can often be neglected when both relations are combined (e.g. into a $k(\theta)$ relation). When computing the saturation deficit curves for the subsoil, both relations have indeed been used. Therefore, hysteresis effects are only considered for the root zone. The factor may vary between zero and two. Sensitivity analysis showed that results are

In order to find out the consequences of changing the hysteretic factor, this factor was given three different values successively: 0.5, 1.0 and 2.0 during the runs for PX11. It turned out that all the results were exactly the same irrespective of the value for this factor.

It depends on where you are on the moisture release curve (= PF-curve). Possibly all the calculated values were not that part of the curve which is sensitive for hysteretic.

For other values and so for other soils it may make a difference.

6 METEOROLOGICAL INPUT DATA AND GROUNDWATER TABLES

6.1 Meteorological inputdata

The observations of the Weed Research Station at Begbroke were used to obtain the meteorological data.

Since the length of the time increment in the MUST-model was one week, the average of the 24 hour means of the meteorological data, mentioned in this chapter, was taken to get the weekly values.

The wind had been measured at a height of 10 metres. In the MUST-model an observation height of 2 metres had been specified, so this value in the set of standard model data was changed. MUST estimated the wind velocity at a height of 2 m from the observed wind velocity u_{10} at height 10 m as follows:

$$u\,(2) = \frac{2u_{10}}{\log\,(10/0.02)} \qquad (5)$$

The fractional duration of sunshine:

$$\text{FRSUN} = \frac{\text{daily hours of sunshine}}{\text{maximum possible hours of sunshine per day}} \qquad (6)$$

The maximum possible hours of sunshine were read from the Smithsonian Meteorological Tables. (List, 1958).

The fractional relative humidity had directly been measured by the Station.

In order to get the mean daily temperature, the mean of the maximum and minimum temperature every day was taken.

The precipitation flux was specified in cm/d. There was a lot of precipitation during the summer months.

Finally the option exists of entering the 24-hour mean net radiation (W/m^2). It is not necessary to give this value. No value was given, therefore the net radiation was calculated by the model.

6.2 Groundwater tables

The depth of the watertable below soil surface had to be specified for each time increment. The water table depth at borehole 0153 had been measured nearly every week. Tensiometers had been measured at the same time interval. The depth of the 6 tensiometers was 10, 30, 40, 60, 80 and 100 cm below soil surface. With the help of the tensiometer observations the water table was calculated in the following way:

assumed: $H = h+z$ (7)

with H = hydraulic head of soil water (m)
h = pressure head of soil water (m)
z = vertical space coordinate (height) (m)

For instance: $H = -0.68$ m at $z = -0.60$ m $h = -0.08$ m
$H = -0.69$ m at $z = -0.80$ m $h = 0.11$ m

h is a linear function of z:

$$h = dz + b$$

with a,b = mathematical coefficient (8)

$$-0.08 = -0.60\ a+b$$
$$-0.11 = -0.80\ a+b$$

$$-0.19 = 0.20\ a \qquad a = -0.94$$
$$b = -0.64$$

at the groundwater table h=0 $z = -b/a = -0.68$. So in this example the groundwater table is 68 cm below soil surface.

It turned out that the tensiometer calculations gave about the same results as the directly measured watertables.

The calulated values were plotted against time and interpolated. Then the daily values were read from the graph and a weekly mean was taken.(Appendix

7. RESULTS OF SOME RUNS OF THE MUST-MODEL

See table 3.

7.1 Standard run with varying hysteretic factor

For the most realistic run of PX11 which was possible at the moment, the meteorological data of appendix H and the waterlevels of appendix J were used, both from 30th April 1985 until 28th October 1985. The soil physical data for this so called standard run are in appendix F, in which you can find the meanings of the program variables too.

Varying the hysteretic factor did not give any different results. Even in October the actual and potential evaporation are still the same. This is because the very wet summer. Summer 1985 is defenitely not representative for a mean Oxfordfloodplain summer!

The PF-value at the rootingdepth of the grass will start to affect the evapotranspiration when the matric pressure at the interface rootzone-subsoil is -100 mbar. Then the actual evapotranspiration is less than the potential evapotranspiration and the grass does not get enough water for an optimal situation.

Another factor that affects the evapotranspiration is the leaf water pressure. When the crop becomes dryer , the canopy resistance will increase. This means that the actual evapotranspiration will become lesser and thus, less than the potential evapotranspiration. P_1 (see appendix D) is -15000 mbar for grass. If the leaf water pressure is higher than -15000 mbar, the canopy resistance has its minimum value. It should be a good thing if the leaf water pressure was added in the output of the MUST-model.

The PF-value at the interface rootzone-subsoil (PFPRS) was for the simulated period between 0.70 and 1.61. This corresponds with 5 to 41 cm of water and a matric pressure of -5 to -41 mbar. This is more than the critical matric pressure at the rootingdepth, since the latter is -100 mbar.

There has been postulated that the soil cover is 100% for grass. Because of that, the soil evaporation is zero.

At time step 1, SUMEPEN (summarized Penman open water evaporationflux) is 1.6 cm. This means that 1.6/2.33 ≈69% of the Penman open

water evaporation flux is equal to the potential (and in these circumstances actual) plant evaporation.
When the actual evaporation is becoming less than the potential one, hysteresis will getting more important.

7.2 The effect of lowering of the watertable

A 20 cm lowering of the watertable increased the saturation deficits of the rootzone and the entire unsaturated zone. For example, at the last timestep the saturation deficit of the entire unsaturated zone was now 11.75 instead of 7.43 cm for the standard run. The actual evaporation was still the same.
The PF-value at the interface rootzone-subsoil was 1.73 and that is sufficient for optimal crop conditions. It is expected that the groundwaterlevel cam lower quite a lot before it starts to affect the vegetation. It was not found out until which level it could lower because of timelack.

7.3 The effect of decreasing the rooting depth

A rootzone of 20 cm instead of 30 cm decreased the saturation deficit in the rootzone but increased the saturation deficit of the entire unsaturated zone (and so the subsoil). Again the actual evapotranspiration equalled the potential evapotranspiration.

7.4 The effect of a profile change

Omitting the silty clay layer, what means a start of the sand/gravel layer at a depth of 43 cm below soil surface,resulted in exactly the same results as the standard run results. But only the first three time steps were simulated!
The output is the same probably because the soil watercontents and the hydraulic conductivities of sand/gravel and silty clay differ not so much.
However , this is not in line with what was expected. The soil physical data were considered as "the most sensitive values" of the MUST-model, An reason for the noticed "unsensitivity" might be that the results of the Marshall program are not reliable.

7.5 Run with the MUST manual data

Since the results of the Marshallprogram are probably not reliable, a run of the MUST-model was done with the in the MUST-manual (De Laat,1985) used data for clay loam and medium fine sand: clay loam: $k=1.0$ to $0.22*10^{-5}$ cm/day ; $\theta=0.445$ to 0.225, medium fine sand: $k=110.$ to $0.43*10^{-5}$ cm/day ; $\theta=0.350$ to 0.023 (The highest values correspond with a matric pressure of 0 mbar, the lowest values with a matric pressure of 16000 mbar).

The following profile was considered: 0-96 cm : clay loam
96+ cm : medium fine sand

All the other data remained the same. Some of the results of this run (and those mentioned in the previous paragraphs of this chapter) are shown in table 3.
The saturation deficits of the rootzone were now considerably lower than those of the standard run, namely 0.86 instead of 3.11 for the first time step.
The saturation deficit of the entire unsaturated zone lowered from 5.83 cm to 3.58 cm in the same period, though the PF-values at the rootingdepth didn't differ from the standard ones.

For all the runs, the saturation deficit of the percolation profile equalled zero.

Table 3. Results of some MUST-model runs

Run	Profile	hyst. factor	D_r (cm)	W (cm)	3th May 1985 SUMETIP cm	SUMETI cm	SR cm	SU cm	SP cm	PFPRS –	25th October 1985 SUMETIP cm	SUMETI cm	SR cm	SU cm	PFPRS –	SP cm
① standard run	0-20 cm loam 20-43 cm clay 43-96 cm silty clay 96+ sand/gravel	1.0	30.	64.	1.6	1.6	3.11	5.83	0.	1.52	32.2	32.2	3.21	7.43	1.61	0.
②	idem	2.0	30.	64.	1.6	1.6	3.11	5.83	0.	1.52	32.2	32.2	3.21	7.43	1.61	0.
③	idem	0.5	30.	64.	1.6	1.6	3.11	5.83	0.	1.52	32.2	32.2	3.21	7.43	1.61	0.
④	idem	2.0	30.	84.	1.6	1.6	3.34	9.95	0.	1.73	32.2	32.2	3.40	11.75	1.77	0.
⑤	idem	2.0	20.	64.	1.6	1.6	2.55	7.15	0.	1.64	32.2	32.2	2.64	8.81	1.71	0.
⑥	0-20 cm loam 20-43 cm clay 43+ cm sand/gravel	0.5	30.	64.	1.6	1.6	3.11	5.83	0.	1.52	n.c	n.c	n.c	n.c	n.c	n.c
⑦	Must-manual data 0-96 cm clay loam 96+ cm medium fine sand	1.0	30.	64.	1.6	1.6	0.86	3.58	0.	1.52	32.2	32.2	0.90	5.13	1.61	0.

n.c. means not calculated

D_r = thickness of rootzone (cm)

W = watertable depth below soil surface (cm)

SR = saturation deficit rootzone (cm)

SU = saturation deficit entire unsaturated zone (cm)

SP = saturation deficit percolation profile (cm)

PFPRS = PF value at rootingdepth

SUMETIP = summarized potential evapotranspiration flux (cm/d)

SUMETI = summarized actual evapotranspiration flux (cm/d)

8 Conclusion

In order to estimate the effect of a groundwaterlevel lowering (because of a gravelextraction) on the vegetation in a Site of Special Scientific Interest (S.S.S.I.) in the Oxford floodplain, the MUST-model is very useful. The model was runned for a location in the scientific interesting site ,Pixey Mead, for a period from 30th April 1985 until 28th October 1985.

The profile was as follows: 0-20 cm loam
20-43cm clay
43-96cm silty clay
96+ sand/gravel

Soil physical data of some other, comparable soils were used. To calculate the hydraulic conductivities for different matric pressures, the model developed by T.J.Marshall (1985) gave larger results than was expected though real measured values were missing. A matching factor to match the calculated and the observed conductivity at saturation for the different may improve the prediction ability. Nevertheless real measurements are necessary, at least in order to compare the results.If that is impossible a better calculation method has to be found.

Even in September and October 1985, the actual and potential evaporation are still the same. This is because the extremely wet summer. Summer 1985 is defenitely not representative for a mean English summer.The results don't rule out that the vegetation will maybe suffer during another (dryer) summer. And then a change in hysteretic factor may slightly affect the results.
Varying the hysteretic factor between 0.5 and 2.0 didn't change something for the year 1985. But that depends on which part of the moisture relieve curve (=PF-curve) is concerned and for other soils it may give different results.
The waterlevel can lower more than 20 cm and the rootingdepth can be shortened from 30 cm to 20cm without affecting the evaporation. In both cases the saturation deficits in the entire unsaturated zone increase, in the former even with more than 70%.
The MUST-model was not sufficiently tested to conclude something about the sensitivity of the model for hydraulic conductivity.
The leaf water pressure is an important factor for the evaporation. It is worth adding this value to the outputresults.

SUGGESTIONS FOR FURTHER RESEARCH

-A more adequate method than the Marshall-program has to be found in order to calculate the hydraulic conductivities for the different standard matric pressures. It is convenient to have a reliable hydraulic conductivity-soilwatercontent relation for the different soillayers. The soilwatercontents and probably the hydraulic conductivities aswell, can be measured even for the high matric matric pressure values (e.i. 16000 mbar-). And thus these can be compared with the calculated ones.

-The soil drainage and the actual evapotranspiration can be measured. The MUST-model results can be checked with these observations

-It is usefull to add the leaf water pressure to the output. Irrigation is not applied. Consequently it can be omitted in the output.

-The model is now only runned for a location were the groundwaterlevel is always in the alluvium. It will be interesting to see what the consequencies are for a location where the groundwaterlevel is always in the gravel or for one where it is sometimes in the gravel, sometimes in the alluvium.

-It will be better to run the model for a dryer summer than 1985.

-It need to be checked if decreasing of the timestep (it was 7 days) will give considerably different results.

-The net-radiation has been measured for the meteorological station at Begbroke. It was an option whether you should give this value for the different timesteps or not. The latter has been done. Thus, the net-radiation was calculated by the model. There was no special reason for this decision. It will be good to see the difference if the net-radiation is input.

-A heading of grass was used. The maximum rooting depth for grass is considered as 30 cm. (De Laat, 1985). Nevertheless many roots were found below this boundary. An option in the model exists for putting in an "own defined" crop (different from the so called

standard crops). This can be done by assigning LU (landuse) a value 8. In this way the rooting depth of grass is not restricted to 30 cm anymore, which seemed rather small.
A heading of cereals is interesting aswell, just for seeing what it will affect.

-The sensitivity of the model with respect to hydraulic conductivity and soil moisture content need to be found out.

-Finally, the heterogener the soil with respect to the hydraulic conductivity, the longer it takes to complete the first run of the model.(Two runs have to be done: the first one for calculating the soil deficit curves). If possible the heterogeneity concerning this parameter has to be limited more or less. In other words: limitation of the different soil layers may reduce the runtime (but may make the results more inaccurate).

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APPENDIX A Upper and lower boundary solution

Upper boundary solution

The saturation deficit curves for the subsoil $S(z_{rs},\bar{q})$ may be written as $S_s(p_{rs},\bar{q})$, because z_{rs} and p_{rs} are for each steady flow $\bar{q}$ related through the pressure profiles $z(p,\bar{q})$. The saturation deficit of the entire unsaturated zone S_u is also a function of p_{rs} and q which follows from

$$S_u(p_{rs},\bar{q}) = S_r(p_{rs}) + S_s(p_{rs},\bar{q}) \qquad (A1)$$

The computation of the steady-state situation at time n + for given initial values S_r^n and S_u^n, and boundary conditions q_s^{n+} and q_w^{n+} that apply over the length of the time increment Δt, proceeds as follows. Calculate S_u^{n+1} from the water balance equation.

$$S_u^{n+1} = S^n + \Delta t(q_s^{n+1/2} + q^{n+1/2}) \qquad (A2)$$

The relations $S_u(p_{rs},\bar{q})$ and $S_r(p_{rs})$ may be combined to give $S_u(S_r,\bar{q})$, so that for $S_u = S_u^{n+1}$ there exists a unique relation between s_r^{n+1} and $\bar{q}^{n+1}$. Another relation between S_r^{n+1} and $\bar{q}^{n+1}$ is provided by the water balance equation for the root zone.

$$S_r^{n+1} = S_r^n + \Delta t(q_s^{n+1/2} - q_{rs}^{n+1/2}) \qquad (A3)$$

assuming that $\bar{q}_{rs}^{n+1/2} = \bar{q}^{n+1}$. Both relations are used to solve S_r^{n+1} and $\bar{q}^{n+1}$ by numerical iteration. The water table depth z_{rs} is found from interpolation in $S_s(z_{rs},\bar{q})$ for $\bar{q} = \bar{q}^{n+1}$ and $S_s = S_u^{n+1} - S_r^{n+1}$.

Lower boundary solution

The model for the lower boundary solution does not consider flow in the upper part of the subsoil. The initial moisture profile serves as the upper boundary of the model. For example, consider the initial moisture profile and corresponding water table at a depth of 85 cm below the upper boundary of the subsoil in Fig. A1 (broken line). The situation is followed by a time increment $\Delta t = 5$ d during which $q_w = -1.0$ cm.d^{-1}. Superposition of the moisture profile for $\bar{q} = -1.0$ cm.d^{-1} on the initial curve yields the soil moisture distribution as shown in Fig. A1.

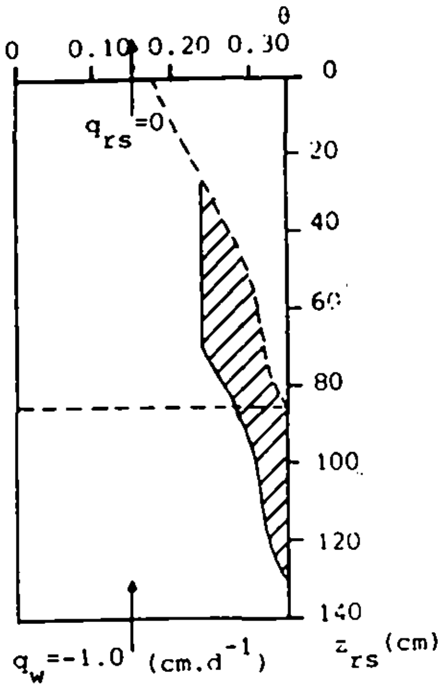


Fig. A1. Moisture profile q=-1.0 cm.d^{-1} superimposed on the initial equilibrium soil moisture distribution (broken line), where the shaded area equals the saturation deficit S_p of the percolation profile (S_p = 5 cm)

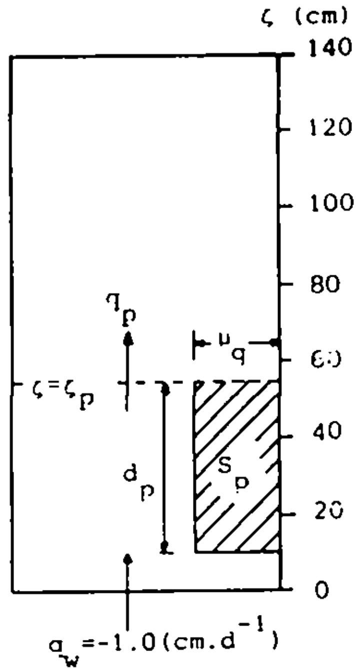


Fig. A2 Schematization of the percolation profile used for the lower boundary solution

Moisture profiles for $\bar{q} < 0$ (steady percolation) show at the upper side a vertical shape. This shape follows directly from Eq. 2, because at a certain height above the water table, where K(p) becomes equal to $-\bar{q}$, the matric pressure, and thus the moisture content, approaches a constant value. The moisture content of the vertical section of the percolation profile is, therefore, related to $\bar{q}$ and since $\bar{q} = -K$, it follows that $\bar{q}(\theta) = -K(\theta)$. Using the relation $\bar{q}(\theta)$ as its inverse $\theta(\bar{q})$, it follows that the storage coefficient $\mu_q = n - \theta(\bar{q})$ with n=porosity. For the most relevant values for $\bar{q}$ occurring in the field (say $-0.1 < \bar{q} < -0.01$ cm.d^{-1}) the relation between μ_q and $\bar{q}$ may often be approximated by

$$\mu_q = A + B \log(-q) \tag{A4}$$

With $\mu_q = n - \theta$ and $\bar{q} = -K$ it follows that

$$\theta = n - A - B \log(K) \tag{A5}$$

The relation between K and θ is either directly measured or derived from the relations K(p) and θ(p). The coefficients A and B are obtained from a linearized plot of log(K) against θ for the section $0.01 < K < 0.1$ cm.d^{-1}.

The shaded area in Fig. A1 is the saturation deficit of the percolation profile S_p, which for the above example equals

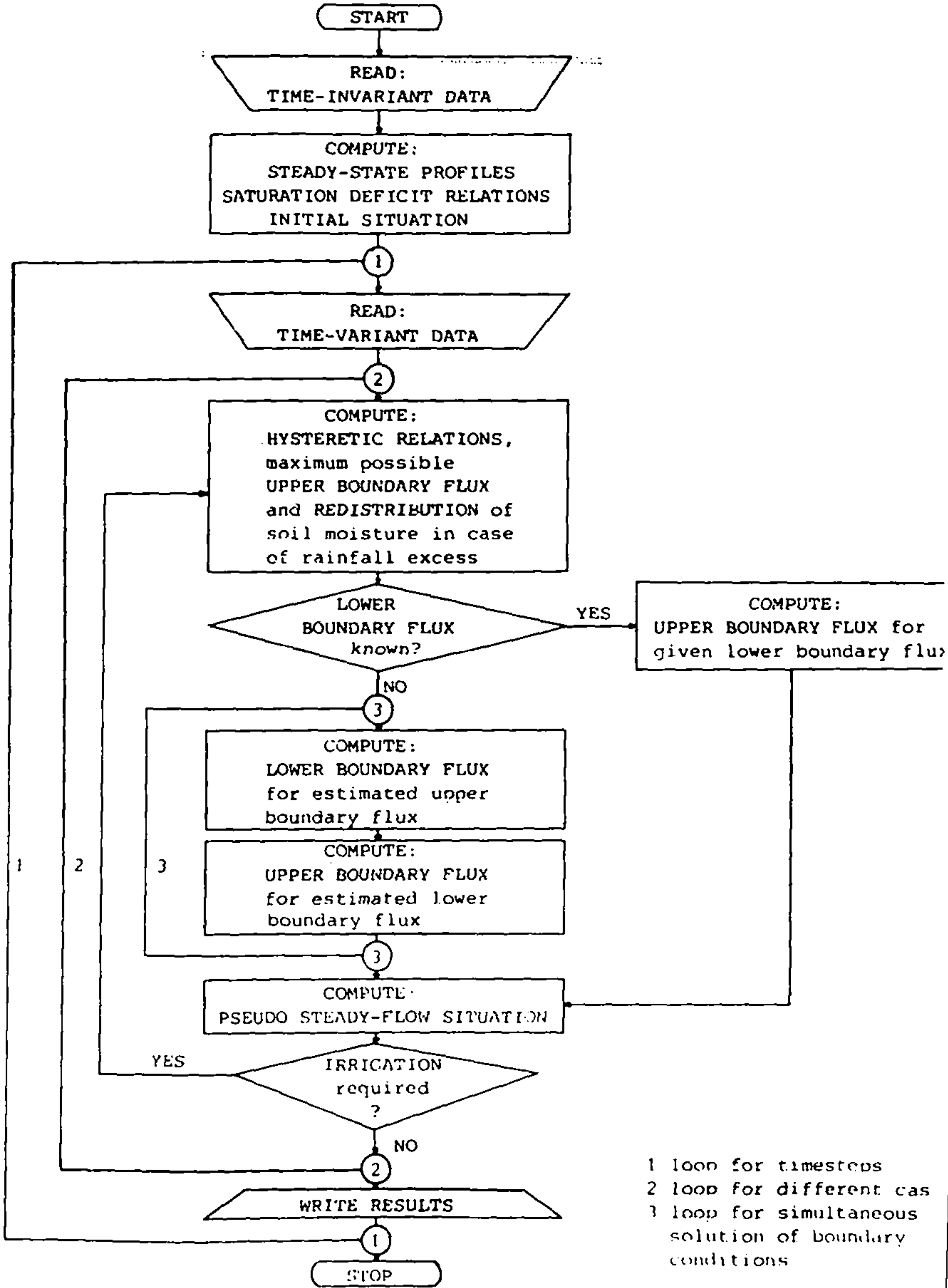
$-\Delta t.q_w = -5 \times (-1.0) = 5.0$ cm. The shape of the percolation profile allows the saturation deficit to be schematized into a rectangle (Fig.A2) with a width μ_q and height $d_p = S_p/\mu_q$. The saturation deficit S_p follows directly from the water balance equation.

$$S_p^{n+1} = S_p^n + \Delta t(q_p^{n+1/2} - q_w^{n+1/2}) \tag{A6}$$

where q_p is the flux across the upper boundary of the percolation profile, the level ζ_p. During periods with capillary rise $q_p \to 0$ while q_p approaches q_{rs} during prolonged percolation. The computation of q_p follows the same procedure as described in this Appendix concerning the upper boundary solution for the solution of q_{rs}, with the difference that the water table depth is assumed at infinity. The value of μ_q follows from Eq. (A4) for $\bar{q} = q_w^{n+\frac{1}{2}}$ so that the water table depth $d_p = S_p/\mu_q$ can be computed.

Combined solution

Transient unsaturated flow is approached by a sequence of steady-state situations corresponding to the upper boundary flux of the subsoil q_{rs}. For capillary rise the assumption of steady flow is seriously violated if the flux across the lower boundary is large in the downward direction so that the actual soil moisture profile has a more elongated shape than the assumed steady-state profile. Therefore, the drawdown of the water table is recalculated assuming steady flow in the lower part of these subsoils correspoding to the lower boundary flux q_w. If the lower boundary solution yields a water table depth below the level found with the steady-state solution for $\bar{q}^{n+1}$, a percolation profile develops. The upper of the percvolation profile ζ_p equals the phreatic level at the time it starts to develop and remains unchanged during the period the percolation profile exists. The difference in the calculated phretic levels is an indication to what extent the steady-state profile for $\bar{q}^{n+1}$ is elongated.



1 loop for timesteps
2 loop for different cas
3 loop for simultaneous solution of boundary conditions

Appendix C

STANDARD MODEL DATA

Standard series of matric pressure values (mbar)

P(1) = 0	P(8) = 250
P(2) = 0	P(9) = 500
P(3) = 10	P(10) = 1000
P(4) = 20	P(11) = 2500
P(5) = 31	P(12) = 5000
P(6) = 50	P(13) = 10000
P(7) = 100	P(14) = 16000

Standard series of steady flow situations ($cm.d^{-1}$)

QBAR(1) = 1.000	QBAR(10) = 0.060
QBAR(2) = 0.500	QBAR(11) = 0.040
QBAR(3) = 0.400	QBAR(12) = 0.030
QBAR(4) = 0.300	QBAR(13) = 0.020
QBAR(5) = 0.200	QBAR(14) = 0.015
QBAR(6) = 0.150	QBAR(15) = 0.010
QBAR(7) = 0.125	QBAR(16) = 0.005
QBAR(8) = 0.100	QBAR(17) = 0.001
QBAR(9) = 0.080	QBAR(18) = 0

APPENDIX D Calculation of the evapotranspiration

The actual evapotranspiration ETI includes the evaporation flux of intercepted water EI, the actual transpiration of flux ET and the actual soil evapotranspiration flux ES, thus

$$ETI = ES + ET + EI \qquad (D1)$$

The precipation flux P may be completely or partly intercepted by the vegetation, so that the flux reaching the soil surface P_s is usually smaller than P. It follows that the maximum possible flux across the soil surface q_s^* may be written as

$$q_s^* = ES + ET - P_s \qquad (D2)$$

Apropiate models for the computation of interception and evapotranspiration are used.
For a certain lower boundary flux q_w, the flux q_s^* is solved with the use of an iterative procedure, which proceeds as follows. First the interception model is executed to compute P_s. Actual evapotrans piration depends on the matric pressure in the rootzone p_{rs}, which value is yet unknown. The procedure therefore starts with the execution of the model for evapotranspiration to calculate ES and ET, using the p_{rs} value of the previous time step. This allows a first estimate of q_s^*. Next, the model for unsaturated flow is executed, using this estimated value for the upperboundary flux, resulting in a better estimate for p_{rs}. The procedure is repeated until the absolute difference in the calculated value of ES + ET for two successive iterations is less than 0.001 cm/d. If the rootzone desiccates to wilting point the actual upper boundary flux q_s follows from the model for unsaturated flow. The value for ES + ET is then computed from Eq. D2 with q_s^* replaced by q_s, which yields

$$ES + ET = q_s + p_s \qquad (D3)$$

The actual evapotranspiration flux ETI is finally obtained with the addition of the evaporation of intercepted water EI as computed with the interception model (Eq. D1).

The computations by the evapotranspiration model proceed as follows (basically the PENMAN formula of Monteith and Rijtema).

The solar radiation R_a reaching the top of the atmosphere is computed for the number of the day in the year DAYN which is halfway along the time increment Δt and for the latitude as specified with the standard model data.

Computation of the short wave radiation R_{sh} reaching the soil surface

$$R_{sh} = R_a \, (a + b.n/N) \qquad \text{(D4)}$$

where n/N is the fractional duration of sunshine. Since the coefficients a and b depend on the location on earth, the values are included for modification in the set of standard model data.

Computation of the net longwave radiation R_{lo} according to a

$$R_{lo} = \sigma(273 + T)^4.(0.47 - 0.67 \; RH.e_s).(0.2 + 0.8n/N) \qquad \text{(D5)}$$

where σ is the Stefan-Boltzmann constant, T is the temperature of the air, e_s is the saturated vapour pressure and RH is the relative humidity, all of which apply at a height of two metres and refer to 24-hour means. The saturated vapour pressure e_s and the slope s of the temperature-saturated vapour pressure curve are computed from the following empirical formulae:

$$e_s = 1.3332 \exp\left(\frac{17.25 \cdot T}{237.3 + T} + 1.51977\right) \qquad \text{(D6)}$$

$$4093.425 \, e_s/(237.3 + T)^2 \qquad \text{(D7)}$$

The evaporation of a wet surface EWET is computed in the units $86400/10\ kg.m^{-2}.s^{-1} = cm.d^{-1}$ as follows

$$EWET = (\frac{86400}{10}) \frac{sR_n/L + \gamma\epsilon\rho_a/p_a(e_s - e_a)/r_a}{s + \gamma} \quad (D8)$$

where L is the latent heat of vaporization, γ is the psychrometric constant, ε is the ratio of molecular weight of water vapour and dry air, ρ_a is the density of air and p_a is the atmospheric pressure. The net radiation R_n follows from

$$R_n = (1 - r)R_{sh} - R_{lo} \quad (D9)$$

where r is the reflection coefficient or albedo. A value for r for each type of land use is included in the set of standard model data. The actual vapour pressure is

$$e_a = e_s \cdot RH \quad (D10)$$

Parameters for the computation of the aerodynamic resistance r_a include the zero-plane displacement d, the roughness length z_0 and the wind velocity u(2+d) at a height of 2 m above the zero-plane. The zero-plane displacement and the roughness length are estimated from the crop height CROPH as follows

$$d = 0.7\ CROPH \quad (D11)$$

$$z_0 = 0.1\ CROPH \quad (D12)$$

The wind velocity u_s observed at a meteorological station in the vicinity at a height HU metres cannot be used directly. A correction factor c_u is required to account for the differences in roughness between the area where the observation station is situated and the study area, and for the difference between the observtion height HU and the standard model height (2 + d). The derivation of this correction factor may be written as

$$c_u = \frac{\ln (60/0.03)}{(HU/0.03)} \quad \frac{\ln (2/z_0)}{\ln (60/z_0)} \tag{D13}$$

The wind velocity at a height of 2 m above the zero-plane u(2 + d) is as follows, calculted from the wind velocity u_s at a as observed at a neighbouring meteorological station

$$u(2 + d) = c_u . u_s \tag{D14}$$

The aerodynmaic resistance r_a follows for all types of land use except for grass and forest from

$$r_a = \frac{1}{k^2 \; u(2 + d)} \quad \{\ln \frac{2}{z_0}\}^2 \tag{D15}$$

where k is the Von Karman constant (0.41). For forests r_a = 10 m.s.$^{-1}$, which value is constant in time.

The aerodynamic resistance for grass follows from the formula of Thom & Oliver

$$r_a = \frac{4.72}{1 + 0.54 \; u(2 + d)} \quad \{\ln \frac{2}{z_0}\}^2 \tag{D16}$$

The actual transpiration for the fraction of soil covered by the crop S_c is computed from

$$ET = \frac{s + \gamma}{s + \gamma(1 + r_c/r_a} \; (EWET - EI/S_c).S_c \tag{D17}$$

where the canopy resistance r_c is a function of the leaf water pressure p_ℓ as shown in Fig. D1.

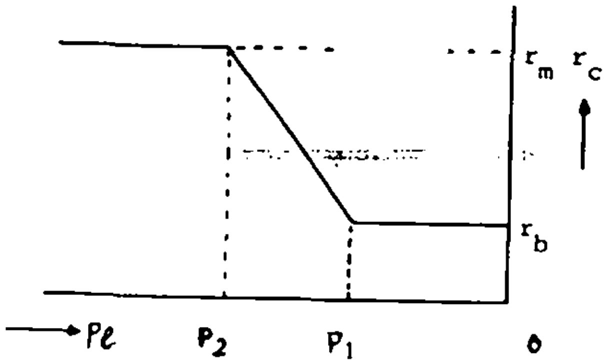


Fig. D.1 The relation between the canopy resistance r_c and the leaf water pressure p_ℓ.

The canopy resistance r_c varies from a minimum value r_b to a maximum value r_m. The mathematical formulation is as follows:

$$r_c = r_b \quad \text{for } p_\ell > p_1 \qquad \text{(D18a)}$$

$$r_c = r_b - (r_b - r_m)\frac{p_1 - p_\ell}{p_1 - p_2} \quad \text{for } p_1 > p_\ell > p_2 \qquad \text{(D18b)}$$

$$r_c = r_m \quad \text{for } p_\ell < p_2 \qquad \text{(D18c)}$$

The empirical constants r_b, r_m, p_1 and p_2 are included in the set of standard model data for each type of land use

The leaf water pressure p_ℓ is computed as

$$p_\ell = p_{rs} - 3ET\,\{(R_{pl} + b/K(P_{rs})\}\rho g/10^4/s_c \qquad \text{(D19)}$$

where R_{pl} is the crop resistance for liquid flow, b is the geometry factor of the root system and $K(p_{rs})$ is the hydraulic conductivity for the matric pressure at the interface root zone-subsoil p_{rs}. Values for R_{pl} are included in the set of standard model data. The geometry factor of the root system is dependent on R_{pl} and the depth of the root zone D_r according to the following formula

$$b = B \cdot \frac{R_{pl}}{D_r} \qquad (D20)$$

The empirical constant $B = 0.04\ cm^2.d^{-1}$.

6. The actual soil evporation for the fraction of soil which is not covered by the crop $(1-S_c)$ is computed from $E_s = \alpha_s\ EPEN\ (1-S_c)$ (D21) where α_s is an emperical constant dependant on the matric pressure in the root zone (Fig. D2) as follows:

$$\alpha_s = 1 - \log(1 - p_{rs})/4.2 \qquad (D22)$$

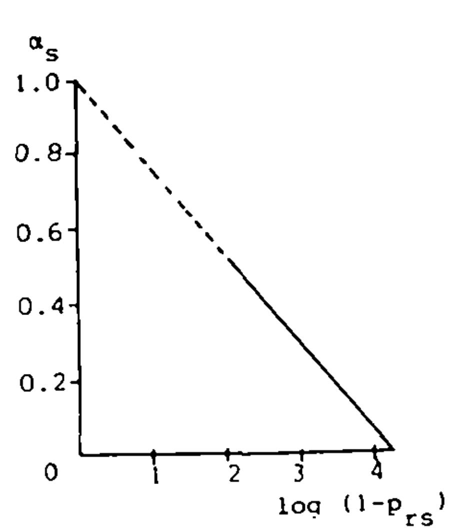


Fig. D2 The relation between the empirical constant α_s and the matric pressure in the root zone p_{rs}(mbar)

The Penman open water evaporation flux EPEN is computed similarly to EWET as

$$EPEN = (\frac{86400}{10}) \frac{sR_n/L + 3.10^{-6} \gamma(0.54\ u(2) + 0.5)\ (e_s - e_a)}{s + \gamma} \qquad (D23)$$

The wind velocity u(2) at the height of 2 m is as follows, estimate from the observed wind velocity u_s at height HU

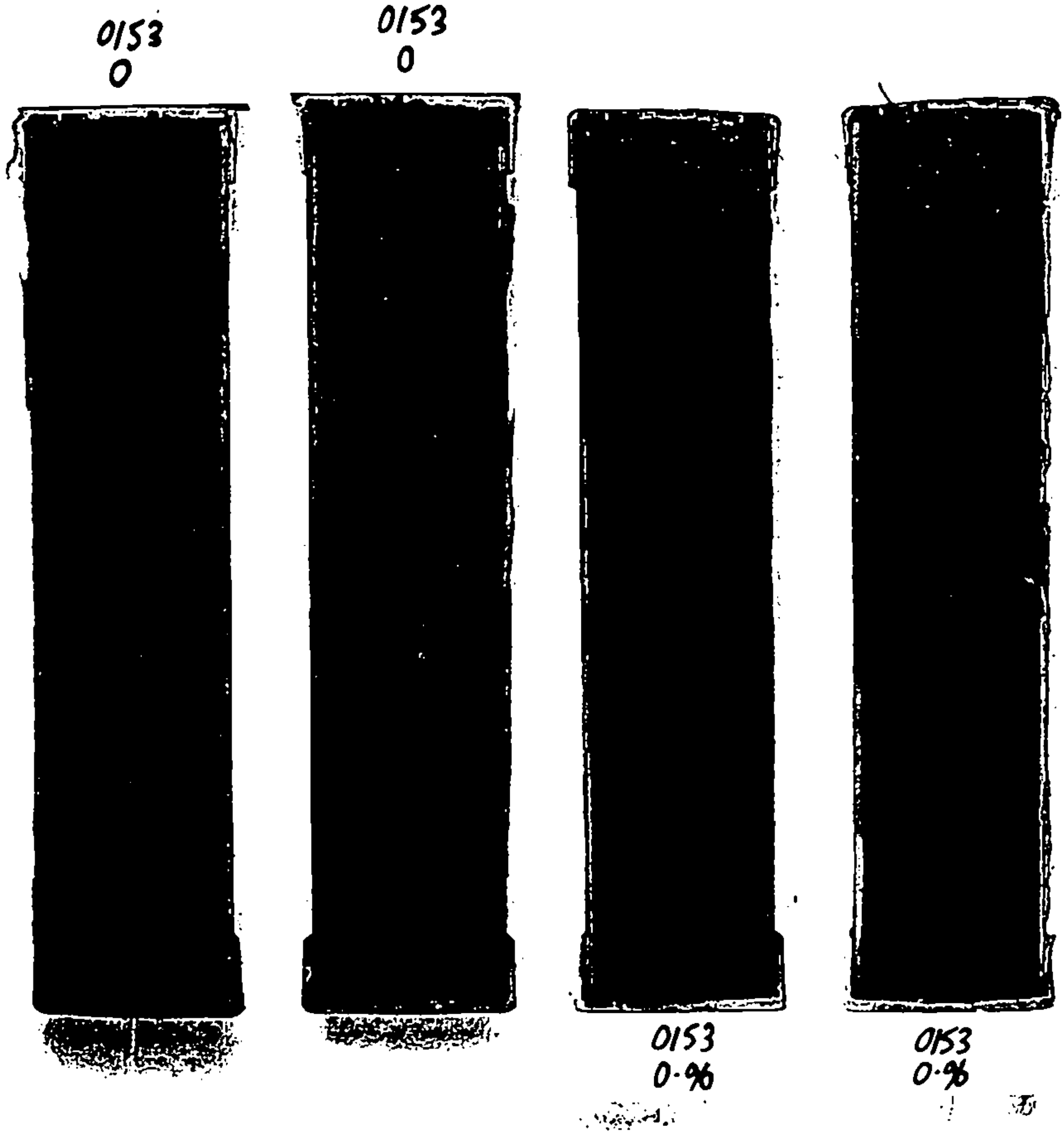
$$u(2) = \frac{2\ u_s}{\log(HU/0.02)} \qquad (D24)$$

The calculation of R_n in Eq. D20 is carried out with a reflection coefficient r = 0.06.

Potential evapotranspiration is defined as the evapotranspiration for p_{rs} = -100 mbar (restricting the evaporation of bare soil to 0.52 EPEN). The computation of potential values for ES adn ET follows exactly the same procedure as described above, but with p_{rs} = -100 mbar.

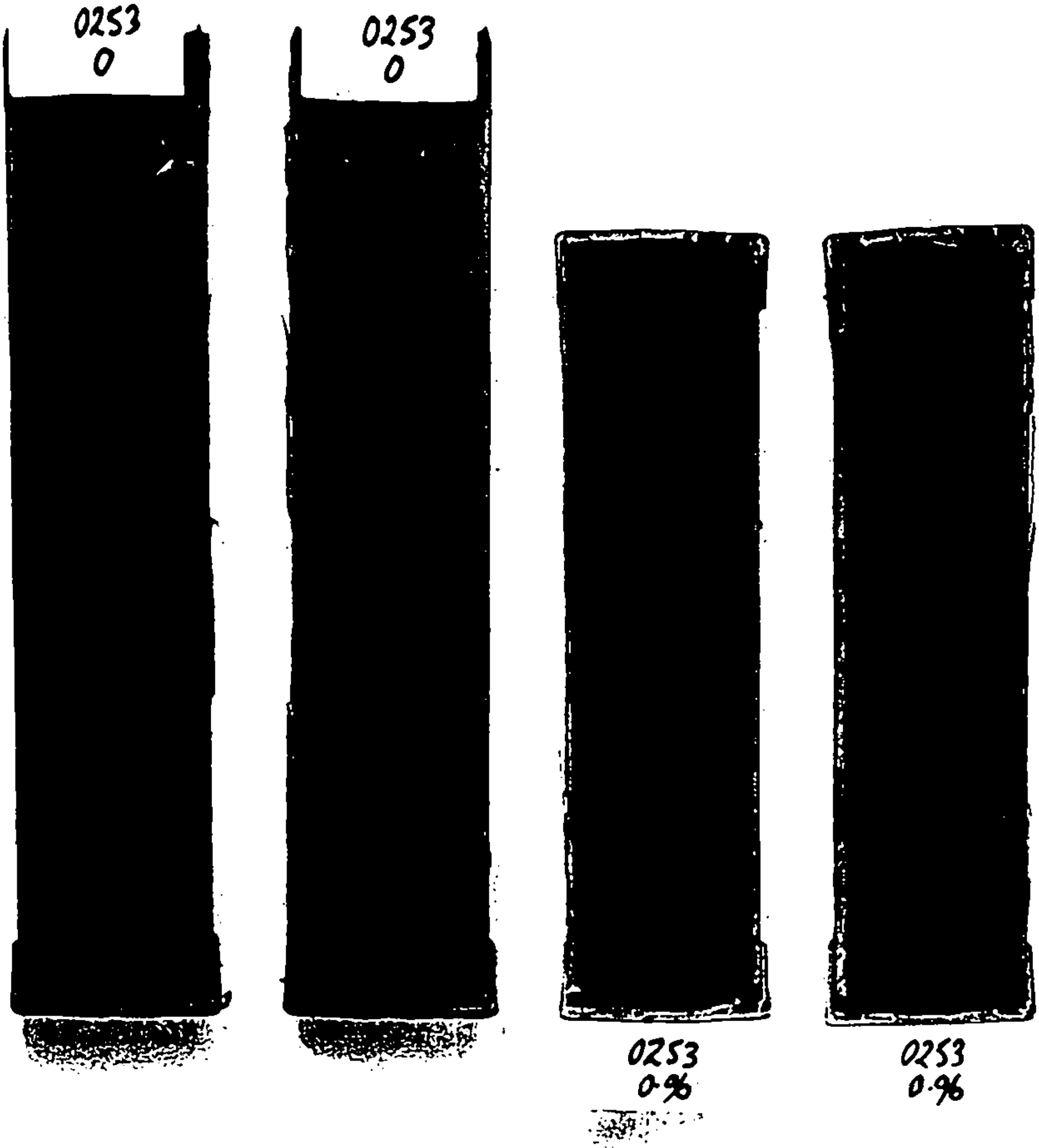
Appendix E
Yarnton Profiles

Borehole 0153



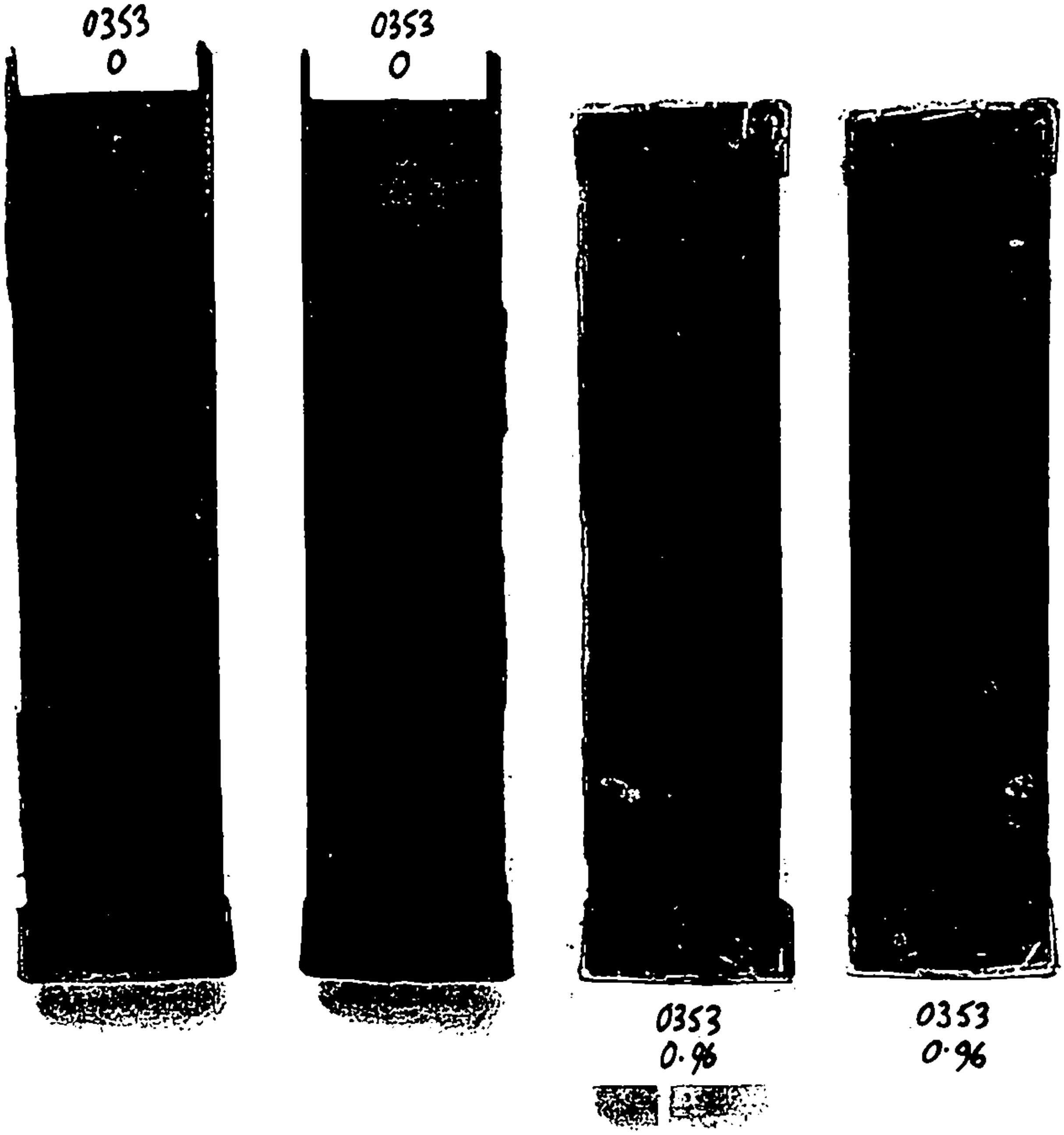
Appendix E continued

Borehole 0253



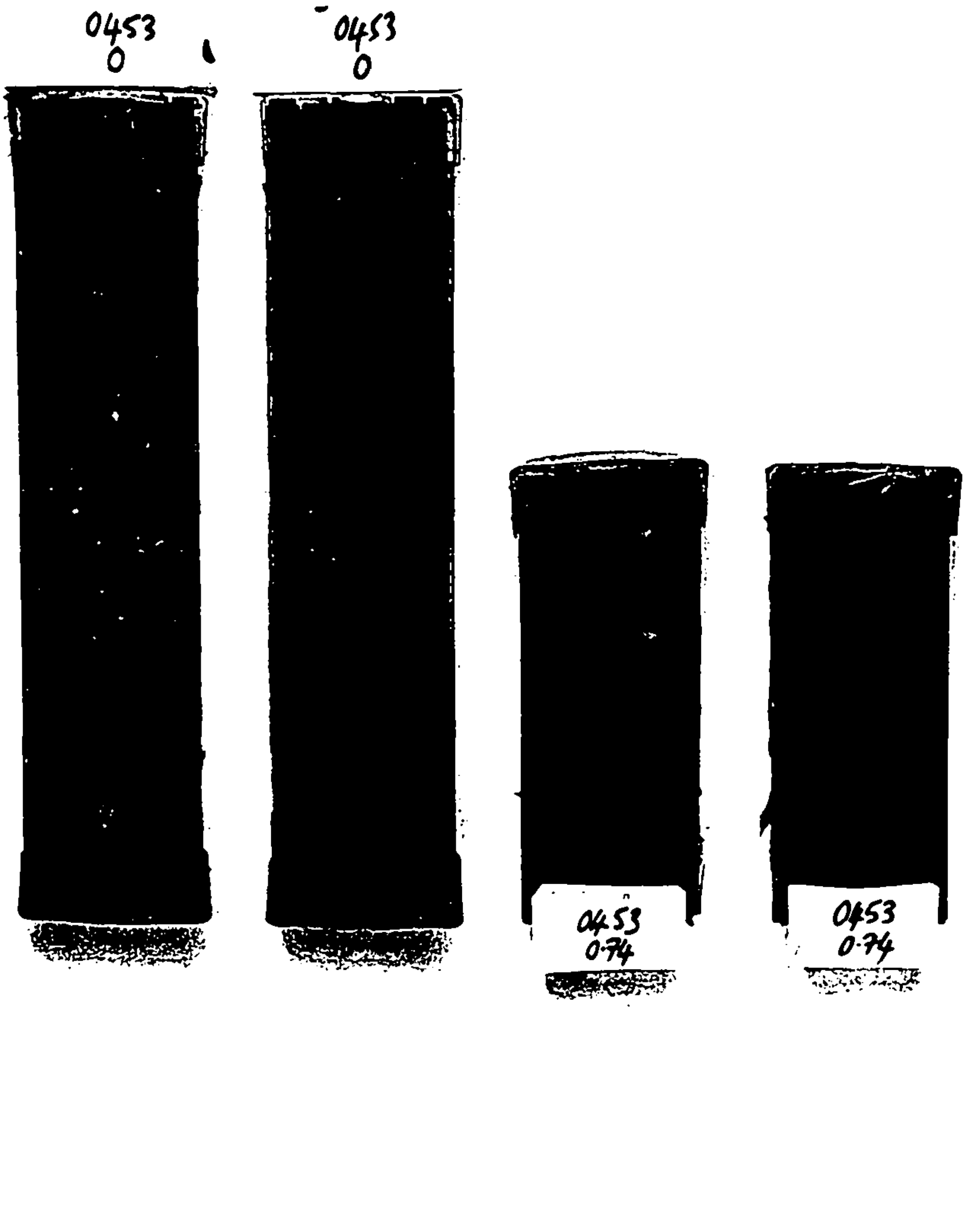
Appendix E continued

Borehole 0353



Appendix E continued

Borehole 0453



APPENDIX F Some soil physical data of the soils comparable with PX11

Profile Number	Series Name	Sub Group	Horizon	Hor Top cm	Hor Bot cm	50mb %vol θ	100mb %vol θ	400mb %vol θ	2bar %vol θ	15bar %vol θ	Total Pores %vol	Bulk Dens g/cm3	Stn %	Fine Sand 60-100 %	Silt 2-60 %	Silt 2-100 %	Clay %	Landuse	comparable layer of PX11 (cm)
SP83/4759	Fladbury	8.13	A	0	15	53.3	51.3	47.1	43.3	35.6	66.0	0.72	0	5	28	-	62	P.Grass	0-20
SP83/4759	Fladbury	8.13	B or C	15	33	56.1	55.3	52.7	45.6	35.7	62.1	1.00	0	1	24		74	P.Grass	20-43
SP83/4759	Fladbury	8.13	B or C	33	62	47.4	47.2	45.5	41.2	39.7	52.2	1.27	0	1	37		61	P.Grass	43-96
SP83/4759	Fladbury	8.13	B or C	62	96	56.8	56.3	54.9	47.0	40.4	59.6	1.07	0	2	21		76	P.Grass	
TF10/2363	Badsey	5.11	A	0	30	35.2	33.9	30.6	25.1	18.4	42.8	1.55	7	13	27		20	Arable	
TF10/2363	Badsey	5.11	A	30	40	31.2	29.4	26.4	23.7	17.3	44.7	1.47	6	13	27		20	Arable	-
TF10/2363	Badsey	5.11	B or C	40	64	25.4	23.3	19.9	14.5	10.6	46.5	1.42	22	6	11		7	Arable	96+

APPENDIX G Results of the Marshallprogram for sand/gravel layer of borehole 0153

Data is for Yarnton , site PX 11
Soil : sand/gravel

Values for hydraulic conductivity against water content from Marshall's model

PF	SUCTION H CM.	WATER CONTENT VOL. FRACTION	HYDRAULIC CONDUCTIVITY CM/DAY
0.74	5.49	0.43179	0.545352E+04
0.87	7.41	0.39857	0.265050E+04
0.98	9.55	0.36536	0.116809E+04
1.13	13.50	0.33214	0.436175E+03
1.30	19.95	0.29893	0.127641E+03
1.60	39.81	0.26571	0.249762E+02
2.00	100.00	0.23250	0.321035E+01
2.60	400.00	0.19929	0.256406E+00
3.00	1000.00	0.16607	0.368188E-01
3.43	2692.00	0.13286	0.381186E-02
4.25	17780.0	0.09964	0.912879E-04
4.95	89130.0	0.06643	0.333670E-05
5.95	891300.	0.03321	0.323951E-07

Equate conductivity with water content not median value of suction.

APPENDIX H

Weekly mean of meteorlogical data at the Weed Research Station, Begbroke

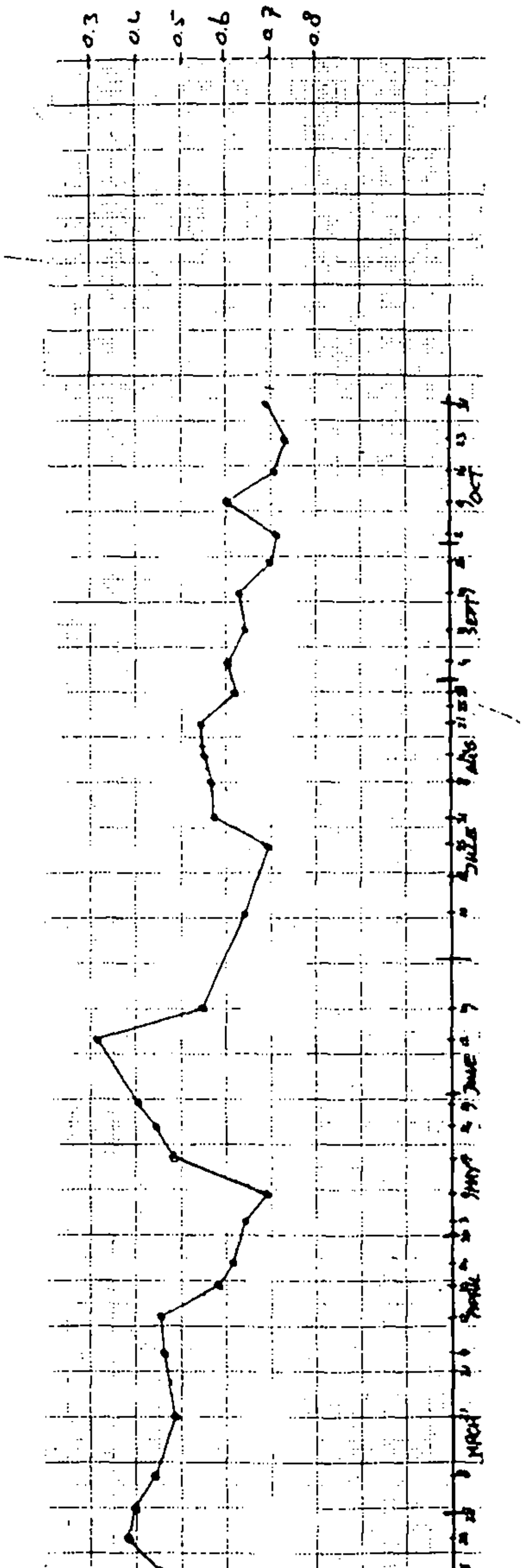
Day number	Windrun m/s**	Fract. dur of Sunsh.	relative humidity %	temperature °C	rainflux cm/d
1- 7 JAN	5.74	0.386	91	0.1	0.02
8-14	3.56	0.196	95	-1.5	0.01
15-21 *	6.71	0.147	100	-1.6	0.22
22-28	5.55	0.245	92	2.5	0.20
29- 4 FEB	6.14	0.205	93	7.8	0.08
5-11	6.58	0.327	95	0.8	0.26
12-18	5.15	0.619	97	-3.7	0.01
19-25	2.74	0.269	91	2.6	0.02
26- 4 MAR *	2.26	0.185	93	5.7	0.13
5-11	4.04	0.463	90	5.7	0.07
12-18	4.85	0.456	84	2.4	0.04
19-25	4.78	0.255	91	2.7	0.24
26- 1 APR	7.49	0.164	86	7.2	0.31
2- 8	7.36	0.234	88	9.8	0.14
9-15 *	6.52	0.363	83	7.7	0.17
16-22	5.11	0.555	77	8.0	0.05
23-29	4.86	0.400	76	5.3	0.14
30- 6 MAY	5.55	0.419	74	8.9	0.01
7-13	6.44	0.279	79	9.2	0.11
14-20	3.71	0.324	88	10.8	0.88
21-27	4.54	0.183	91	10.2	0.47
28- 3 JUN *	5.18	0.814	74	11.6	0.00
4-10 *	2.75	0.300	74	10.6	0.84
11-17 *	2.61	0.290	76	10.2	0.15
18-24	2.13	0.200	86	12.0	0.43
25- 1 JUL *	5.45	0.558	76	13.3	0.14
2- 8 *	3.51	0.227	69	15.7	0.00
9-15 *	4.28	0.131	78	15.6	0.07
16-22 *	6.52	0.081	71	14.0	0.19
23-29	5.01	0.084	86	16.2	0.42
30- 5 AUG *	6.02	0.085	83	13.7	0.39
6-12 *	6.00	0.068	85	12.9	0.30
13-19	4.54	0.037	85	13.0	0.30
20-26	2.28	0.110	82	11.9	0.15
27- 2 SEP	2.04	0.062	84	12.9	0.01
3- 9	1.63	0.097	84	11.9	0.02
10-16	1.46	0.135	82	12.7	0.03
17-23	1.89	0.021	87	13.8	0.05
24-30	0.78	0.104	88	14.4	0.00
1- 7 OCT	4.62	0.355	79	13.3	0.46
8-14	2.96	0.410	81	9.8	0.02
15-21	1.46	0.175	86	8.7	0.01
22-28	1.37	0.276	79	6.3	0.01

Some data are missing and/or estimated

** wind velocity has been measured at 10 m height

Appendix. –

Graph of observed waterlevels at PX11 (from 1st Jan. 1985 – 31st Oct. 1985)



Appendix J

Weekly means of water levels of PX11 from 1st January 1985 until 28th October 1985.

Day number in 1985	Weekly mean of daily water levels
1- 7 JAN	0.466
8-14	0.541
15-21	0.584
22-28	0.585
29- 4 FEB	0.561
5-11	0.514
12-18	0.450
19-25	0.391
26- 4 MAR	0.400
5-11	0.439
12-18	0.467
19-25	0.481
26- 1 APR	0.473
2- 8	0.460
9-15	0.471
16-22	0.574
23-29	0.619
30- 6 MAY	0.643
7-13	0.654
14-20	0.501
21-27	0.441
28- 3 JUN	0.391
4-10	0.368
11-17	0.379
18-24	0.548
25- 1 JUL	0.586
2- 8	0.618
9-15	0.647
16-22	0.671
23-29	0.660
30- 5 AUG	0.574
6-12	0.502
13-19	0.547
20-26	0.564
27- 2 SEP	0.612
3- 9	0.613
10-16	0.636
17-23	0.644
24-30	0.699
1- 7 OCT	0.672
8-14	0.633
15-21	0.714
22-28	0.718