INSTITUTE of HYDROLOGY

Application of the MUST model to the test sites Yarnton Mead and Hupselse Beek

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CONTENTS

The MUST model was thought to be a suitable model and some work was done by Geharda Tamminga, but through lack of data and time she did not finish the project. This study is partly a continuation of her work, but as there are more input data measurements available, the modelling of Yarnton Mead should be more correct.

The Hupselse Beek area is a hydrological test area in the Netherlands. This area has been (and still is) monitored for several years as a part of the IHD Leemingbeek. For some sites all the input data for the MUST model are known and also some data which MUST should give as output (ie. potential evapotranspiration) so this is an ideal area to investigate the sensitivity of the model for various inputs.

In Chapter 2 a brief description of the Hupselse Beek area and of Yarnton Mead is given. Chapter 3 deals with the theory of the MUST model and Chapter 4 with Marshall's method for computing hydraulic conductivity. In Chapter 5 the working method is explained and the results of this study you will find in Chapter 6. The conclusions are given in Chapter 7.

PREFACE

This is a report of a 3 month practical period at the Institute of Hydrology, Wallingford, England.

I would like to thank Tr H. Gumadjeng and C.M.K. Gardner, PhD, for their support and advice.

Arjan Nass

ABSTRACT

This report presents the results of some simulations with the MUST model. MUST is a model for flow above a shallow water table. The runs have been made for two test sites, one in England (Yarnton Mead) and one in the Netherlands (Hupselse Beek area).

The sensitivity of the model for variations in various input data has been researched. It has been found that the model is not very sensitive to a change in the lenght of the timestep from 1 to 7 days and also not to a change of the parameter PFA in the evapotranspiration reduction relationship. The model is somewhat more sensitive to a change in hydraulic conductivity values and depending on the type of soil and meteorological circumstances, can be very sensitive to a change in the depth of the root zone.

Further is found that MUST does a very good computation of the potential evapotranspiration, but that the computation of the actual evapotranspiration is less accurate. The computed actual evapotranspiration seems to be too high.

The simulations done for the Hupselse Beek area show that the different types of soil which can be found there have no great difference in behaviour, that is response to the meteorological circumstances.

Runs that have been made for the Yarnton Mead profile indicate that at least for wet years, the groundwater table can be lowered till 250 cm below soil surface without having a great effect on the evapotranspiration.

INTRODUCTION

MUST is a model for unsaturated flow above a shallow water table.

The aim for this study of MUST is twofold:

- investigate the sensitivity of the model for various input data
- run the model for two sites of special scientific interest (SSSI), one in England (Yarnton Mead), and one in the Netherlands the (Hupselse Beek area)

The sensitivity of the model to variations in the following input data has been investigated:

- the timescale
- the number of different layers in the subsoil
- the hydraulic conductivity of the layers in the subsoil
- the depth of the root zone
- the parameter PFA in the evapotranspiration reduction relation (when potential evapotranspiration is given).

The sites of specific interest for which MUST has been run are Yarnton Mead and the Hupselse Beek area.

Yarnton Mead is an SSSI because of its vegetation and the possibility exists of gravel extraction in the neighbourhood. It is expected that the groundwater level will be lower, but shallow confined groundwater levels may be of significance to the protection of the plant communities at Yarnton Mead.

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 SSSI's. It was the intention to predict the consequences of engineering works in advance of any gravel extraction. During a hydrological 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.

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).

?. BRIEF DESCRIPTION OF THE HUPSELSE BEEK AREA AND THE YARNTON TEST SITE

HUPSELSE BEEK AREA

The Hupselse Beek area is situated in the Province of Geldrerland in the east of the Netherlands, just to the north of the town of Groenlo (see Figure 1). The area covers 6.5 km^2. The landscape is undulating; its altitude varies between 24 and 33 meters above mean sea-level. Land use is predominantly agricultural (72% grassland, 14% arable land, 6% woodland, 7% built up area and roads, and 1% water).

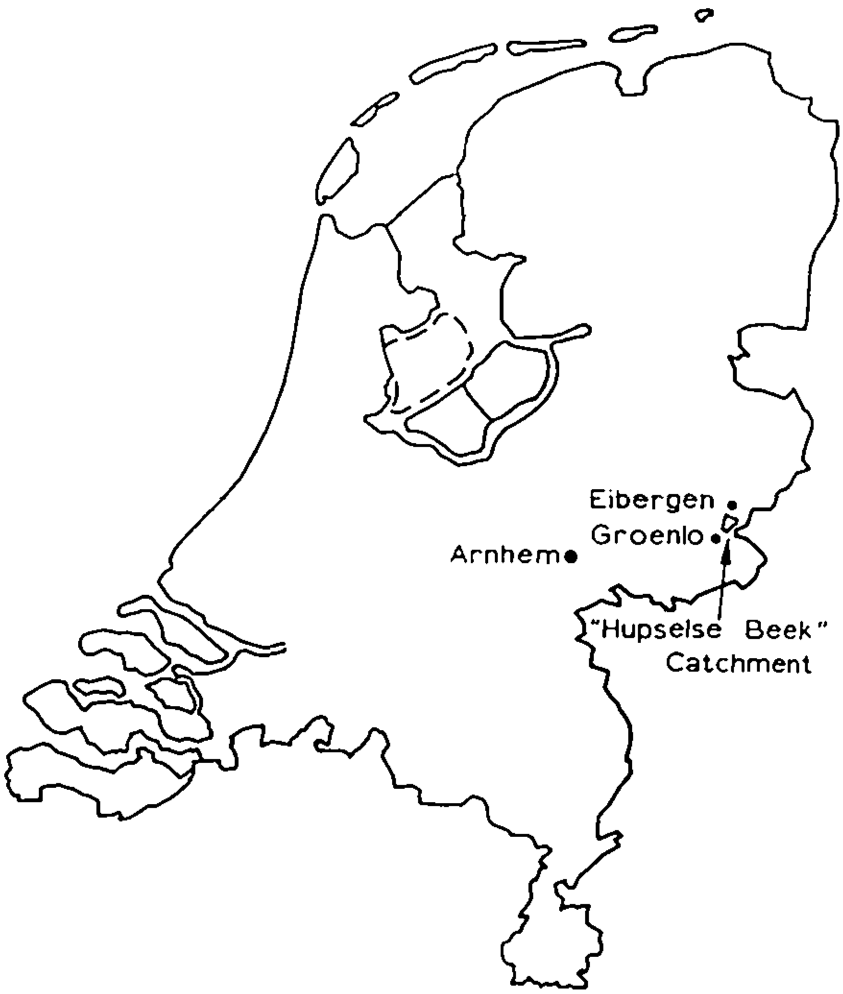


FIG. 1 Situation of the Hupselse Beek catchment

2.1.1 Geology of the Hupselse Beek area

The most important geological formations which can be found at or near the surface in this area are of Miocene, Middle Pleistocene and Late Glacial age. The Miocene series consist of fine sandy, mica- and pyrite containing, bluish-black marine clays.

Only in the eastern part of the area is it found at or near the surface. In a western direction it disappears below younger deposits. In the Middle Pleistocene the Rhine-system deposited over a wide front a coarse sandy, gravel-rich material. This material mixed with components of eastern origin, is called the Formation of Sterksel-Enschede. The series has been eroded very strongly so that the terrace is highly dissected. The western boundary of this dissected terrace lies somewhere west of the Groenlo-Eibergen road. The thickness of the terrace varies between some metres and a maximum of about 8 metres; it lies on top of the Tertiary subbottom. In the Saalian the inland ice penetrated the Hupsel area. So the whole area, including the terrace and marine-Miocene was covered with till. During the melting of the inland ice, but also during the periglacial climate this material was exposed to strong erosion, so that nowadays only remnants of it can be found.

West of dissected terrace-boundary the landscape lies clearly lower. The presence of till in the sub-surface indicates that there was an ice-lobe in this depression during the Saalian (near Ruurlo about 20 m below sea level).

During the Weichselian the sands of the Kreftenheye Formation were deposited by the Rhine-system.

In the Late Glacial period the eolian sedimentation dominated the fluviatile so that over great parts of the area coversand was deposited. The differences in thickness cause the undulating landscape.

For most of the area the presence of till (or till remnants) is of great significance to the relatively small water-storage capacity of the profile (the available groundwater level contour maps confirm this). The till deposit lies about 1 metre below the surface. It forms a kind of plaster over the dissected terrace. As a result of erosion, however, there are several leaks in the till-plaster.

Horizontal variation of permeability that causes an elevation of the groundwater level occurs in the coversand area adjacent to the terrace. The groundwater discharge in this area is demonstrated by soppy bottom conditions. This feature is reinforced by the lower topographic position of the coversand area.

The value of the hydraulic conductivity is strongly dependent on the level of the water table and varies between ca. 20 m^2/d in the eastern part of the area till ca. 350 m^2/d in the north-west (time-mean).

Figure 2 shows a schematic geological cross section of the area and Table 1 gives the litho-stratigrafie.

2.1.2 Nature of the soils in the Hupselse Beek area

The main soils in the Hupselse Beek area are Typic Haplaquod and Typic Haplaquepts (Wösten et al., 1985).

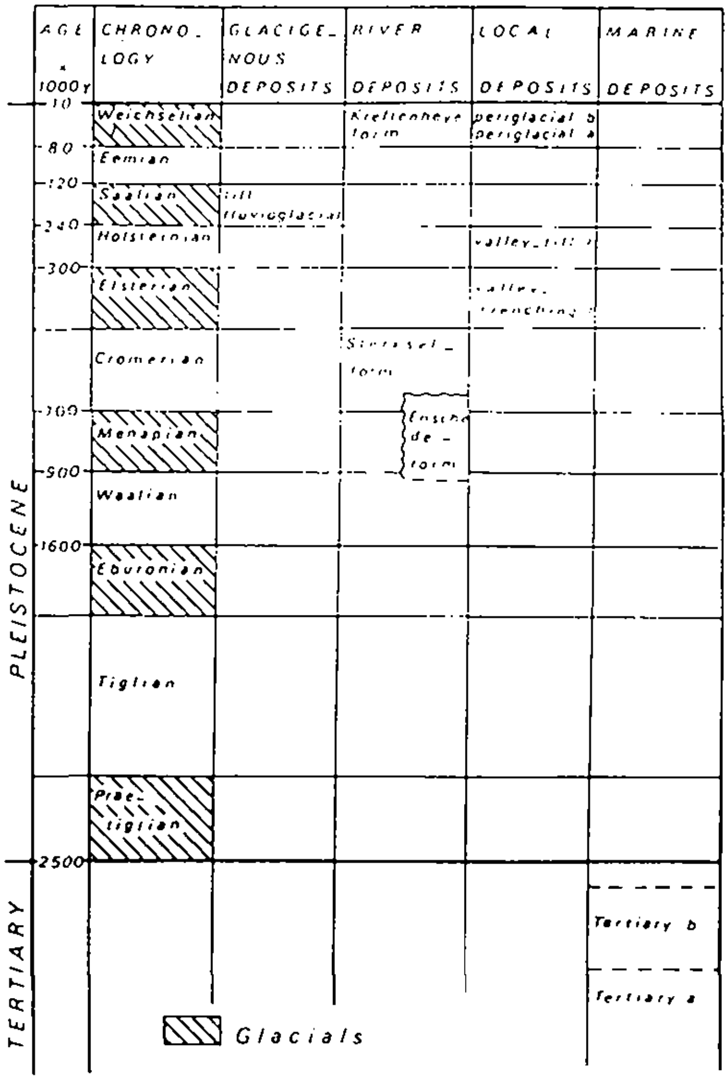
Typic Haplaquods are soils of which the upper layer is less than 30 cm thick and consists of loam and poor loamy fine sand. This type of soil makes up the largest part of the area (74%). Locally much gravel and coarse sand can be found.

In the area three different Typic Haplaquepts can be found. The first type has a humus upper layer less than 30 cm and no B-horizon. The upper layer consists of light loamy fine sand on a little coloured underground. The percentage of loam can be higher if clay is present at shallow depths. This type of soil makes up ± 24% of the area.

The second type is a sandy soil with a humus upperlayer thicker than 50 cm and has developed through century-long upbringing of moorland and dung. The soil is dark coloured, a light loamy fine sand and the water management is mostly good. It makes up 2% of the area.

The third type can only be found on some places in the area. The humus holding rusty upper layer is thin and consists of light loamy respectively loamy fine sand on a bleached grey subsoil. There is no B-horizon.

TABLE 1 Litho-stratigraphy for the Hupsel area



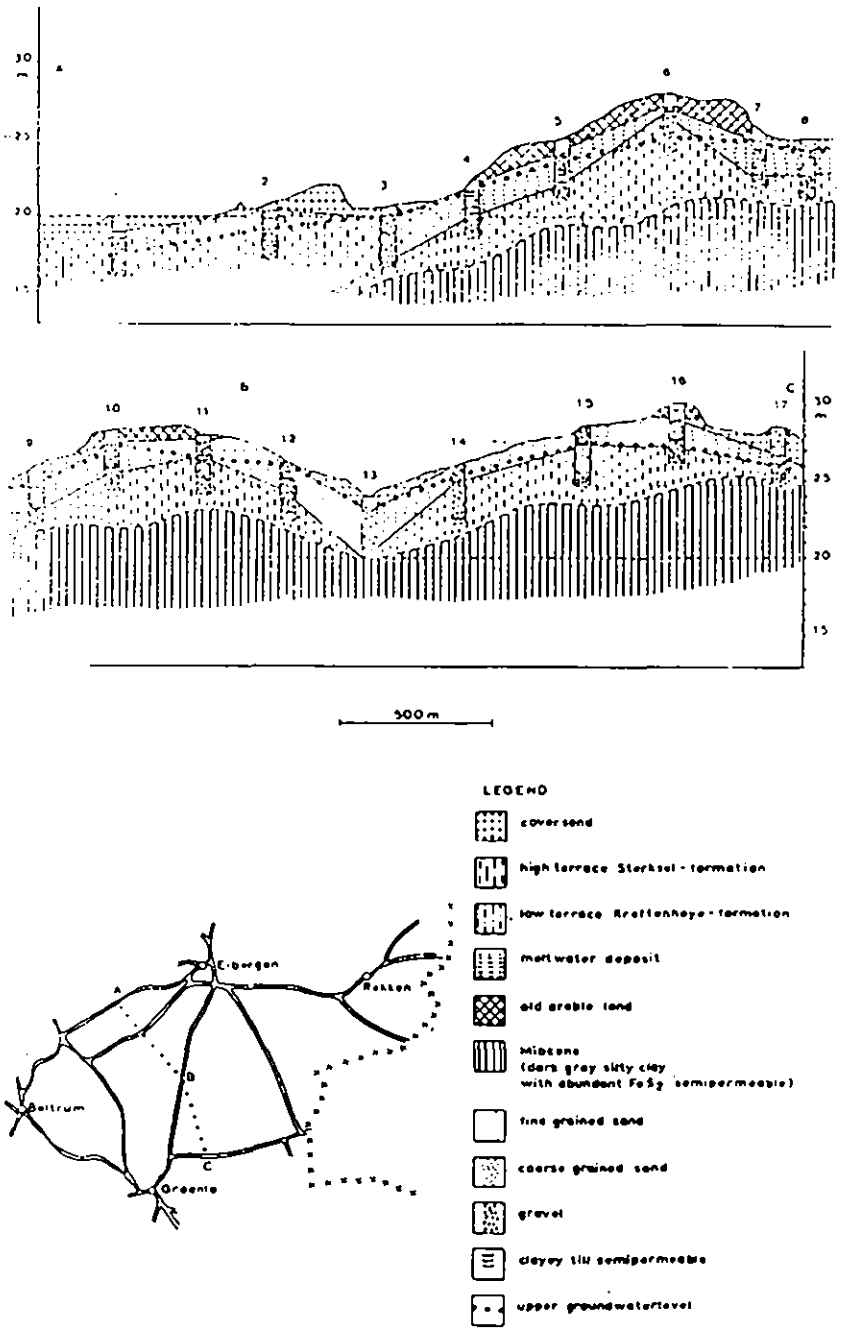


FIG.2 Schematic geological cross section through Hupsel area

2.2 THE YARNTON TEST SITE

2.2.1 Geology

The Yarnton test site can be found near Oxford (see Figures 3 and 4). The test site and most of the region around it is dominated by the Thames Valley with its Quarternary Alluvium and river terrace deposits overlying mesozoic Oxford Clay (see Figure 5).

The alluvial aquifer which borders the Thames in this region, comprises First or Floodplain Terrace deposits 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.

Most of the Thames floodplain is mapped as alluvial. 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.

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).

Table 2 gives the strata in the Oxford district.

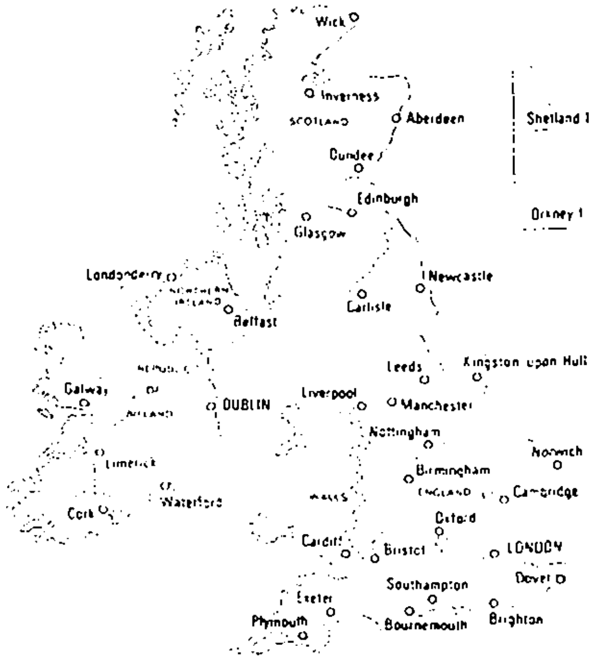


FIG.3 Location of the Yarnton test site near Oxford (*)

FIG.4 Location of the Yarnton test site in greater detail

TABLE 2 Table of strata in the Oxford district

Eras	*Systems*	*Formations*
QUATERNARY OR PSYCHOZOIC	HOLOCENE	Alluvium, peat, tufa.
	PLEISTOCENE	River gravels. Glacial drift. The Pebble Gravel.
TERTIARY OR CAINOZOIC	PLIOCENE	Gravels and sands of the 600-ft. Chiltern platform. Fossiliferous sandstone of Rothamstead.
	EOCENE	Bagshot Beds. London Clay. Reading Beds.
SECONDARY OR MESOZOIC	CRETACEOUS	Upper { Chalk. Upper Greensand. Gault. Lower { Lower Greensand. Wealden Beds.
	JURASSIC	Upper { Purbeck Beds. Portland Beds. Kimeridge Clay. Corallian Beds. Oxford Clay. Mid { Great Oolite Series. Inferior Oolite Series. Lower { Upper Lias. Middle Lias. Lower Lias.
	TRIASSIC	Rhætic Beds. Keuper Marls } Not at surface nr. Oxford.
PRIMARY OR PALAEOZOIC	CARBONIFEROUS	Coal Measures } Not at surface nr. Oxford.
	SILURIAN	Ludlow Beds. } Not at surface nr. Oxford.
	CAMBRIAN	Tremadoc Slates. } Not at surface nr. Oxford.

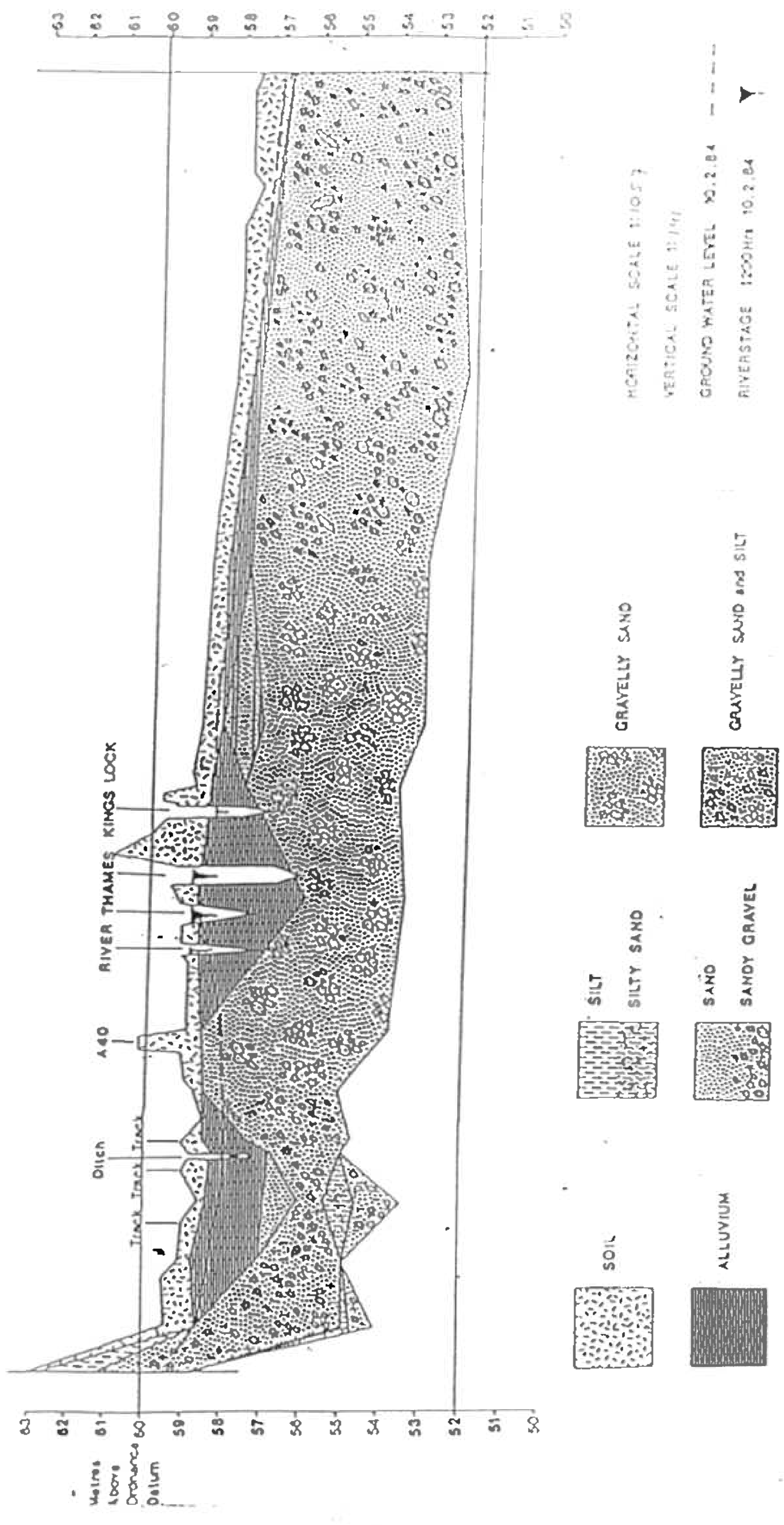


FIG. 5 Geological cross section

FIG. 5 Geological cross section

2.2.2 Geohydrology

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 Lock groundwater flow is quite different and unexpected. The surface of the groundwater body is saucer shaped with radial flow inward.

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 is an area of confined aquifer. The shallowest depth to groundwater is less than 0.5 m.

THE MUST MODEL

MUST 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. Therefore MUST is not appropriate for process study purposes. 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 very little computer time and allows simple data management for its execution.

Theory

Richards (1931) derived the following equation for unsaturated flow in non-homogeneous, isotropic, porous media

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(\frac{K(p)}{\rho g}\frac{\partial}{\partial x} + \frac{\partial}{\partial y}\left(\frac{K(p)}{\rho g}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{K(p)}{\rho g}\frac{\partial p}{\partial z}\right) + \frac{\partial K(p)}{\partial z} \qquad (1)$$

where x, y and z are the co-ordinate directions (m)

- t = time (s)
- p = matric pressure (Pa)
- K = hydraulic conductivity ($m^3 s^{-1}$)
- g = acceleration due to gravity ($m\ s^{-2}$)
- l = density of water ($kg\ m^{-2}$)
- θ = fractional volumetric moisture content ($kg\ kg^{-1}$)

As flow in the unsaturated zone is predominantly in the vertical direction, it is in general sufficient to consider one dimensional vertical flow, for which Eq. (1) is reduced to

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(\frac{K(p)}{\rho g}\frac{\partial p}{\partial z}\right) + \frac{\partial K(p)}{\partial z} \qquad (2)$$

A further simplification of the general Eq. (1) is obtained when considering steady flow conditions. For this situation, Eq. (2) reduces to Darcy's law for steady flow in the vertical direction. This pseudo steady-state approach has been developed over the last 25 years. The solution technique for unsaturated flow used by the simulation model MUST is based on the pseudo steady-state approach. A comprehensive description of the solution method is given by de Laat (1980); the principles are outlined below.

3.1 PSEUDO STEADY-STATE APPROACH

The equation for steady vertical flow may be written as

$$\bar{q} = -K(p) \left(\frac{1}{\rho g} \frac{dp}{dz} + 1\right) \tag{3}$$

where the steady flux $\bar{q}$ (m s^{-1}) is taken positive upwards.

Separating the variables and solving for z gives

$$z = -\frac{1}{\rho g} \int_0^p \frac{k(p)}{\bar{q} + K(p)} \, dp \tag{4}$$

where the reference level is chosen at the stationary phreatic surface at which level $z = 0$ and $p = 0$. The relation between p and z for a particular steady flux $\bar{q}$ is termed pressure profile $z(p,\bar{q})$. Given the relation between moisture content and matric pressure $\theta(p)$, known as soil moisture characteristic or pF-curve ($pF = \log(-p)$), pressure profiles are easily transformed into moisture profiles $z(\theta,q)$.

The schematization of the flow system is shown in Figure 6.

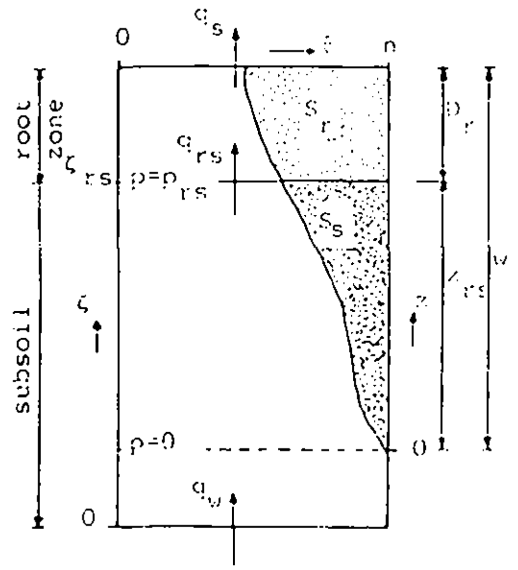


FIGURE 6. Schematic presentation of the unsaturated flow system

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[m] equals zero at the lower boundary and is taken as positive in upward direction. The upper layer in which most of the roots are present is termed root zone and the remaining part of the unsaturated zone is called subsoil. Though the simulation model may be used for situations where different soil physical data apply to different layers, Figure 1 shows a homogeneous soil profile for which the maximum soil moisture content or porosity is n. The depth of the root zone is constant and equals D_r[m] while the interface between the root zone and the subsoil is at a height ζ_{rs}[m]. The flux across the interface between the root zone and the subsoil is denoted by 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 [m s^{-1}].

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 $\bar{q}$. It should be noted that the level for z = 0 (the phreatic level) changes with time, depending on the value for z_{rs}[m] the distance between the lower side of the root zone and the water table. Integration of the pore space in the subsoil not filled with water gives the saturation deficit of the subsoil S_s. Systemic integration of moisture profiles for many values of z_{rs} yields for each steady flow situation $\bar{q}$ a relation between S_s and z_{rs}, which relations together form the saturation deficit curves for the subsoil $S_s(z_{rs},\bar{q})$.

The depth of the water table below soil surface is w. At the phreatic level p = 0 and at the height $\zeta=\zeta_{rs}$ the matric pressure is denoted by p_{rs}.

It is assumed that the water extraction by the crop is such that the soil moisture distribution in the root zone approximates an equilibrium situation at all times, so that $dp = \rho g dz$. For a given matric pressure at the interface root zone - subsoil p_{rs}, the soil moisture distribution in the root zone is known, and the saturation deficit S_r is found by integrating that pore space not filled with water. Systematic integration for a number of p_{rs} values yields the saturation deficit curve for the root zone $S_r(p_{rs})$.

3.2 UPPER BOUNDARY SOLUTION

The saturation deficit curves for the subsoil $S_s(z_{rs},\bar{q})$ may alternatively be written as $S_s(p_{rs},\bar{q})$. The saturation deficit of the entire unsaturated zone S_u is also a function of p_{rs} and $\bar{q}$ which follows from

$$S_u(p_{rs},\bar{q}) = S_r(p_{rs}) + S_s(P_{rs},\bar{q}) \tag{5}$$

where S_u = saturation deficit of the entire unsaturated zone [m s^{-1}]

S_p = saturation deficit of the root zone [m s^{-1}]

S_s = saturation deficit of the subsoil [ms^{-1}]

p_{rs} = matric pressure at the interface root zone-subsoil [Pa]

The computation of the steady-state situation at time n + ½ for given initial values S_r^n and S_u^n, the boundary conditions $q_s^{n+½}$ and $q_w^{n+½}$ that apply over the length of the time increment Δt, proceeds as follows. Calculate S_u^{n+1} the water balance equation

$$S_u^{n+1} = S_u^n + \Delta t(q_s^{n+½} - q_w^{n+½}) \tag{6}$$

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.

$$S_r^{n+1} = S_r^n + \Delta t(q_s^{n+½} - q_{rs}^{n+½}) \quad (7)$$

assuming that $\bar{q}_{rs}^{n+½} = \bar{q}^{n+1}$. 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 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}.

The solution is termed upper boundary solution because the soil moisture distribution and the water table depth are determined by the flux across the upper boundary of the subsoil. This flux is the difference between rainfall reaching the soil surface and the upward flux resulting from transpiration of vegetation and evaporation of bare soil. The maximum upper boundary flux q_s^* may be either specified for each time increment or calculated from meteorological data. However, there may be two different reasons which do not allow the flux q_s^* actually to occur: (i) the root zone is almost saturated and the flux q_s^* which is in downward direction is too large for the incoming amount of water to be stored in the root zone; (ii) the root zone is desiccated to wilting point and the upward flux q_s^* is larger than the capillary rise from the subsoil to the root zone. In both cases the actual flux q_s^* will differ from the maximum flux q_s^*.

(i) If the root zone becomes saturated, the remaining volume of water which cannot be stored in the root zone is assumed to run off overland. The programme can be changed such that water on the surface will not run off, but remain for infiltration in the next time step. A saturated root zone does not imply that the subsoil is also saturated, because the (saturated) hydraulic conductivity may not allow a rapid percolation of water from the root zone into the subsoil. For this situation the model calculated a water table which is below the root zone, while there is still water on the surface. Hence, MUST may compute a perched water table, but only with regard to the interface root zone - subsoil.

(ii) If the root zone desiccates to wilting point the actual upper boundary flux q_s becomes equal to the capillary rise of soil moisture from the subsoil to the root zone q_{rs}. For this situation the actual upper boundary flux q_s is less that q_s^*. Hence the evapotranspiration which was either specified or computed by the evaporation model is then reduced by an amount which is equal to the difference between q_s^* and q_s.

For capillary rise ($q_{rs} > 0$) in combination with downward flow across the lower boundary ($q_w < 0$), the flow situation in the subsoil cannot be approximated by a single-steady-state situation. For relatively large negative values of the flux across the lower boundary the position of the water table is dominated by the shape of the moisture profile in the lower part of the subsoil rather than the profile for capillary rise. The pseudo steady-state approach is, therefore, applied to both boundary flux conditions separately.

3.3 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.

Moisture profiles for $\bar{q} < 0$ (steady percolation) show at the upper side a vertical shape. This shape follows directly from Eq. (4), because at the 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 profiles 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 $\mu_q = n - \theta(\bar{q})$. 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

$$\mu_q = A + B \log(-\bar{q}) \qquad (8)$$

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

$$\theta = n - A - B \log(K) \qquad (9)$$

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 saturation deficit S_p follows directly from the water balance equation

$$S_p^{n+1} = S_p^n + \Delta t(q_p^{n+½} - q_w^{n+½}) \qquad (10)$$

where S_p = saturation deficit S_p[m s^{-1}]
q_p = the flux across the upper boundary of the percolation profile, the level ζ_p in [m s^{-1}].

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 Chapter 3.2 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. (8) for $\bar{q} = q_w^{n+½}$ so that the water table depth d_p = S_p/μ_q can be computed.

An example of the lower boundary solution is given in Appendix 1.

3.4 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 the sub-soil corresponding 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 boundary of the percolation 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 phreatic levels is an indication to what extent the steady-state profile for $\bar{q}^{n+1}$ is elongated. 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.

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 (eg. into a K(θ) 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. Since data on hysteresis in the soil moisture characteristic are usually not available, a 'hysteresis factor' is introduced, defined as the number of logarithm cycles over which the $S_r(p_{rs})$ curve for drying is shifted along the P_{rs} axis to obtain the wetting curve. In the absence of data the hysteresis factor must be calibrated.

NOTE: The unit used in MUST is [cm d^{-1}] rather than [m s^{-1}].

THE HYDRAULIC CONDUCTIVITY OF WATER IN SOIL AS COMPUTED BY MARSHALL'S METHOD

One of the ways to calculate the unsaturated hydraulic conductivity of a soil for varying degrees of saturation is by the method developed by T J Marshall (Marshall, 1958). The basis of the calculation method is Kozeny's equation for intrinsic permeability, adapted by Marshall to water content versus suction, and modified to produce hydraulic conductivity.

Kozeny's equation gives:

$$= \epsilon^2/s^2 \; k \quad [cm^2] \tag{11}$$

where = intrinsic permeability in $[cm^2]$

ϵ = porosity $[cm^3/cm^3]$

s = surface area of particles in $[cm^2/cm^3]$

k = a constant

This equation is modified to use pore size distribution instead of particle properties as a basis. When applied to the flow of liquid through unsaturated material the liquid filled pores are conducting and the air filled pores are excluded from the calculation, so that porosity in turn is replaced by volume concentration c (cc/cc), ie. moisture content, and pore radius is replaced by suction h (cm). When applied to the flow of water through soil, intrinsic permeability is converted to hydraulic conductivity by multiplying the numerical constant by g/η

where g = acceleration due to gravity $[m/s^2]$

η = dynamic viscosity (kg/ms)

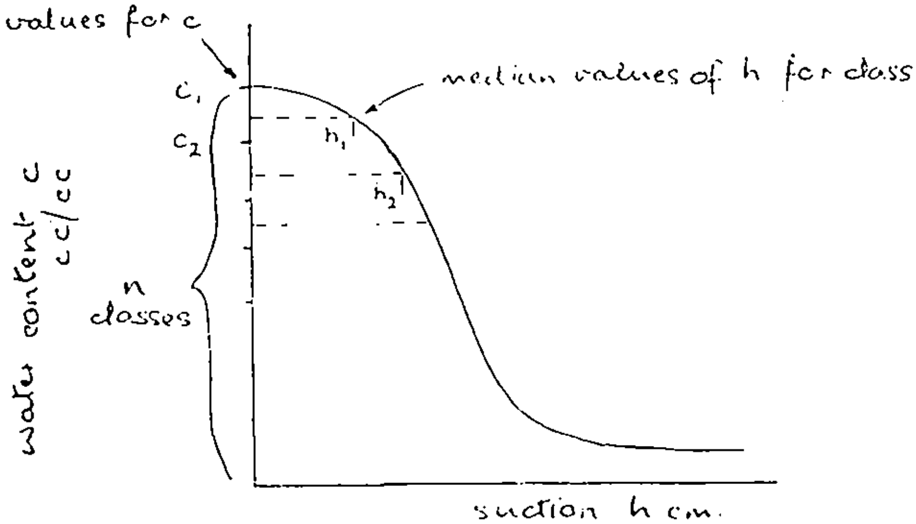


Fig.7 A cumulative curve of pore space plotted against $1/h^2$

For the cumulative curve of pore space plotted against $1/h^2$ a series of possibility classes (n) is set up. If n is sufficiently large, there is negligible error in taking the suction h to correspond to the mean water content c in each class (ie. the mean suction in each class). The equation finally becomes:

$$K^1 = 2.7 * 10^2 * c^2 \times n^{-2} \left[\frac{1}{h_2^1} + \frac{3}{h_2^2} + \frac{5}{h_2^2} + \ldots + \frac{(2n-1)}{h_n^2}\right][cm/s] \quad (12)$$

where k^1 = hydraulic conductivity [cm/s]

c = water content $[cm^3/cm^3]$

h = suction in [cm]

n = number of classes

NOTE: h_1 is corresponding to the largest pore, h_n is corresponding to the smallest pore.

Equation (12) was found too high values for the hydraulic conductivity so a matching factor was introduced.

The matching factor is K_s/K_{sc} where K_s is the observed and K_{sc} is the calculated hydraulic conductivity at saturation.

5. WORKING METHOD

5.1 CHANGES IN THE INPUT AND OUTPUT OF THE MUST MODEL

While learning to understand the MUST program, it was found that the necessity to give the input data in a fixed format was time consuming and error prone, so a program was written to deal with this problem (see Appendix 2). It takes into account the different options with which you can run MUST (de Laat, 1985) and you can give the input data in a free format. Because of this input program, the format of some input data for the MUST program had to be changed! Appendix 3 gives an index of the input data for MUST in the new format and Appendix 4 gives the input data for the three examples given by de Laat, 1985 with this new format. If you do not make use of the input program, you will have to present the data to MUST in this format.

When you run MUST you get a lot of output data. A plot program was written for a better and easier way of understanding these results. It gives you plots of the rainfall, potential and actual evapotranspiration (in the same figure), the saturation deficit of the root zone, the water table depth below soil surface and the lower boundary flux, all plotted against the time. MUST has been changed in order to give the index data for this plot program.

5.2 COLLECTING OF THE INPUT DATA

The required input data for MUST can be distinguished in

general input data
soil physical input
meteorological input
hydrological input.

For the Hupselse Beek area all the necessary data were available. A report of STIBOKA (Institute of Soil Survey) provided the soil input data for 7 different soil profiles, representing 4 different soil types (Wösten et al., 1983). Appendices 7 and 8 show a survey of the measured K-h relations and soil water characteristics (data points) with a drawn regression line. Figure 7 shows the situation of the profiles in the area.

For the meteorological data the data of the meteorological station Assink were used. This station is situated in the area. Data were available for the period 25.2.1976 to 31.12.1984.

The water table depths were recorded for each profile on a 2-weekly basis and, for the profile Assink test site, on a daily basis too.

For Yarnton Mead of the soil physical input data, alone the soil moisture content had been measured, the soil hydraulic conductivity had to be computed. This was done with Marshall's method, partly because Geharda Tamminga had already some some work using this method and partly because a computer program that used this method was available. A arbitrary matching factor of 0.01 was used for fitting the computed hydraulic conductivities to more reasonable values (no value for the saturated soil hydraulic was known).

Three other sets of soil physical data are used. These sets were obtained by comparing the different soil layers of the Yarnton Mead profile with soil layers described in STIBOKA report (Wösten et al., 1986). This report gives for different types of soil layers the soil moisture content and the hydraulic conductivities for values of the matric pressure varying from 0 to 1.10^7 cm.

The meteorological data for 1985 were obtained from the Weed Research Station at Begbroke and for 1986 from the Radcliffe Observatorium at Oxford. The Smithsonian Meteorological tables have been used to compute the fractional duration of sunshine, as alone the sun duration was recorded.

Watertable depths were available on a weekly basis.

SCALE 1:25,000

FIG.7 Location of the seven test sites in the Hupselse Beek area

	Brom test site	a Typic Haplaquod
	Assink test site	a Typic Haplaquod
3	Lensink	a Typic Haplaquepts, second type
4	Assink farmland	a Typic Haplaquod
5	Ten Barge	a Typic Haplaquod
6	Schuurmans	a Typic Haplaquept, first type
7	Faaks	a Typic Haplaquept, first type
8-12	Additional locations where soil samples have been taken	

5.3 RUNNING THE MODEL

5.3.1 Running MUST with Hupsel data

The sensing of MUST for the following factors has been researched with Hupsel data:

(a) the timestep
(b) the conductivity of the layers in the subsoil
(c) the depth of the root zone
(d) the reduction factor for evapotranspiration, (PFA).

ad a) For the profile Assink test site, a typic Haplaquod soil, runs have been made with a timestep of 1 day and 7 days.

ad b) MUST has been run for the profile Assink test site (timestep 1 day) with different sets of hydraulic conductivity data for the layers in the subsoil, while keeping the rest of the input data the same (of course). Runs have been made with the measured soil hydraulic conductivity (s.h.c.) for each different layer as input, with the measured s.h.c. values of the B-horizon used as s.h.c. values for all the layers and with computed s.h.c. values for each different layer as input. These last conductivities were computed according to a relation given by Bloemen (Bloemen, 1980).

ad c) 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 effect evapotranspiration; should this be the case later in the season, the roots are already fully developed. The land use of Assink test site is grass. De Laat, 1985, gives 30 cm as a maximum rooting depth for grass. MUST has been run with this working depth altered to 25 and 35 cm for the profile Assink test site, timestep 1 day.

ad d) When you give the potential evapotranspiration as input to the program, PFA is the parameter in the evapotranspiration reduction relation which gives the point where actual evapotranspiration becomes less than the potential evapotranspiration. De Laat, 1985, gives as value for PFA 2.7 (matric pressure = 500 cm). Runs have been made for the profile Assink test site (timestep 1 day) with a value for PFA of 2.4, 2.7 and 3.0 (matric pressure = 250, 500 cm and 1000 cm respectively).

Also runs have been made for the profile Assink test site for the period 25.2.1976 to 30.12.1982 (timestep 1 day) and for the 7 different profiles in the Hupselse Beek area for the periods 1.4.76 to 29.9.1976 and 1.4.1977 to 29.9.1977 with a timestep of 7 days. These 'summer half-years' have been chosen because nearly all the evapotranspiration takes place in these periods. 1976 was a very dry year, 1977 an average year. No measurements of a wet year were available.

One of the options of MUST is that the model comprises the level of the groundwater table when you give as input data a lower boundary flux groundwater table level relationship and a start value for the water level. It was the intention to run MUST with this option but a proper flux-level relation could not be found, so this has not been done.

5.3.2 Running MUST with the data of Yarnton Mead

MUST has been run for Yarnton Mead for the period 2.4.1985 to 28.10.1985 and 2.4.1986 to 30.9.1986. The timestep was 7 days. This has been done for five different sets of soil physical input data. These sets are:

The soil physical input data as given by Geharda Tamminga, 1986, but with measured soil water characteristic data for the root zone.

Soil physical input data with measured soil moisture contents for the different layers and soil water characteristic data values as computed for the different layers with Marshall's method.

3/4/5. Three different sets of soil physical data obtained out of the STIBOKA report (see Chapter 5.2).

Appendix 5 contains these 5 different sets of soil physical input data, and Appendix 6 gives a survey of the conductivities of the different layers.

The sensitivity of MUST for the following factors has been research with Yarnton Mead data:

(a) The number of different layers in the subsoil

(b) The conductivity of the layers in the subsoil

(c) The depth of the root zone

(d) The reduction factor for evapotranspiration, PFA.

Ada and b) The sensitivity of the MUST model for the number of layers and the conductivities of those layers can be seen by comparing the runs with the different STIBOKA input sets.

ad c) The sensitivity of MUST for the depth of the root zone is researched by using the input data sets 2 and 3 and changing the root zone to 20, 40 and 50 cm. The land use of Yarnton Mead is grass and roots can still be found at those depths.

ad d) The influence of the reduction factor FPA on the computation of the actual evapotranspiration (as you give the potential evapotranspiration as an input data) has been researched with sets 2 and 3 of the soil physical input data and values of 2.4, 2.7 and 3.0 for PFA.

As the intention was to investigate the effects of a lower groundwater table on the plant communities of Yarnton Mead, runs have been made with the groundwater table lowered to 80, 100, 120 and 140 cm below soil surface for the whole period. For the sets 2 and 3 of the soil physical input data the watertable was even lowered to 250 cm below soil surface. This may be done because the level of the groundwater is dominated by the Thames and the Thames is a controlled river. The soil physical input data (sets 2, 3, 4, 5) and the meteorological data were kept the same.

5. RESULTS

6.1 RESULTS OF THE SENSITIVITY INVESTIGATION

In order to assess the effects of changing the various input data mainly the cumulative potential (EPOT) and actual (EACT) evapotranspiration as computed by the different model simulations were compared.

NOTE: EPOT and EACT are ETip and WT1 in the output of MUST.

Changing the timestep from 1 to 7 days had almost no effect on the computed potential and actual evapotranspiration for the profile Assink test site as can be seen in Table 3.

TABLE 3 Computed cumulative potential (EPOT) and actual (EACT) evapotranspiration in cm for the period 1.4/1.10 1976 and 1977 for the profile Assink test site. Timesteps 1 day and 7 days.

	Timestep 1 day		Timestep 7 days	
	EPOT	EACT	EPOT	EACT
1976	50.1	35.4	49.6	37.0
1977	36.8	36.8	36.8	36.8

The effect of changing the root zone depth depends on the type of soil and the meteorological data as can be seen in Table 4. A change in the root zone depth had no effect on the Assink test file profile in 1977, but a change of 5 cm in the root zone depth for this same profile in 1976 gives a difference of ± 10% in actual evapotranspiration. For Yarnton Mead the effect of a change in root zone depth is not so big. The water content of the root zone is higher than the water content of the root zone for the Assink profile and 1985 and 1986 were both wet years.

TABLE 4a Effect of a change in root zone depth on the computed cumulative actual evapotransporation (cm) for the profile Assink test site.

Depth of root zone	1.4/1,10 1976 EPOT	EACT	1.4/1.10 1977 EPOT	EACT
25	50.1	32.4	36.8	36.8
30	50.1	35.3	36.8	36.8
35	50.1	40.0	36.8	36.8

TABLE 4b Effect of change in root zone depth on the computed cumulative actual evapotranspiration (cm) for the profile Yarnton Mead.

Depth of	Set 2 soil physical data				Set 3 soil physical data			
root zone	2.4/28.10 1985		2.4/29.9 1986		1.4/28.10 1985		2.4/29.9 1986	
	EPOT	EACT	EPOT	EACT	EPOT	EACT	EPOT	EACT
20	37.3	37.3	44.3	44.3	37.3	35.9	44.3	35.2
30	37.3	37.3	44.3	44.3	37.3	37.3	44.3	38.4
40	37.3	37.3	44.3	44.3	37.3	37.3	44.3	40.6
50	37.3	37.3	44.3	44.3	37.3	37.3		

The influence of the hydraulic conductivity values on the computed actual evapotranspiration is shown in Table 5. Table 5a shows the result of the model simulations with different hydraulic conductivities for Assink test site, while Table 5b shows the result of the model simulations with the 5 different sets of soil physical input data for Yarnton Mead. See Appendix 5 for these soil physical input data.

TABLE 5a Effect on the computed cumulative actual evapotranspiration (cm) of a change in hydraulic conductivity values for Assink test site.

	Set 1		Set 2		Set 3	
	EPOT	EACT	EPOT	EACT	EPOT	EACT
1.4/1.10 1976	50.1	35.3	50.1	31.2	50.1	26.1
1.4/1.10 1977	36.8	36.8	36.8	36.8	36.8	35.4

SET 1 : measured hydraulic conductivity values

SET 2 : values as measured for the B-horizon taken as values for all the layers

SET 3 : hydraulic conductivity computed according to Bloemen.

TABLE 5b Effect on the computed cumulative actual evapotranspiration (cm) of a change in hydraulic conductivity values for Yarnton Mead.

	Set 1		Set 2		Set 3		Set 4		Set 5	
	EPOT	EACT	EPOT	EACT	EPOT	EACT	EPOT	EACT	EPOT	EACT
2.4/28.10 1985	37.3	37.3	37.3	37.3	37.3	37.3	37.3	37.3	37.3	37.3
2.4/29.9 1986	44.3	44.3	44.3	44.3	44.3	38.4	44.3	39.7	44.3	39.0

SET 1 : Geharda's data

SET 2 : Measured soil water characterisatic data - conductivities computed by Marshall's method

SET 3 : Stiboka data 1

SET 4 Stiboka data 2

SET 5 Stiboka data 3

The model simulation for the profile Assink test site for 1976 shows that if there is a reduction in evapotranspiration, this reduction will be greater if the conductivity is less. The conductivity of Set 2 is less than the conductivity of Set 1 and the conductivity of Set 3 is less than the conductivity of the Sets 1 and 2. The simulation for the Yarnton Mead profile shows the same results (see also Chapter 6.3). For a wet year the exact value of the hydraulic conductivity at a certain matric pressure is not so important, as long as the order of magnitude is correct (at least for the profile Assink test site and Yarnton Mead).

Table 6 shows that the effect of a (small) change of the parameter PFA in the evapotranspiration reduction relationship has a very small effect on the computed cumulative actual evapotranspiration. The difference between the actual evapotranspiration is less than 5%. No indication was found of a shift in evapotranspiration through the period.

TABLE 6 Effect of a change of the parameter PFA in the evapotranspiration reduction relationship on the computed cumulative actual evapotranspiration (cm) for the profile Assink test site and Yarnton Mead.

	ASSINK TEST SITE				YARNTON MEAD SET 2				YARNTON MEAD SET 3			
	1.4/1.10		1.4/1.10		2.4/20.10		2.4/29.9		2.4/20.10		2.7/29.9	
	1976		1977		1985		1986		1985		1986	
PFA	EPOT	EACT	EPOT	EACT	EPOT	EACT	EPOT	EACT	EPOT	EACT	EPOT	EACT
2.4	50.4	34.1	36.3	36.3	50.7	50.7	55.5	55.5	50.7	49.1	55.5	46.0
2.7	50.4	34.7	36.3	36.3	50.7	50.7	55.5	55.5	50.7	50.2	55.5	46.3
3.0	50.4	35.3	36.3	36.3	50.7	50.7	55.5	55.5	50.7	50.7	55.5	48.6

NOTE; The potential evaporation data given in Table 6 are not, as before, computed by the model but given as input to the model ('measured' values). For Assink test site the difference between the potential evapotranspirations as computed by the model and the measured values is negligible. In 1976 computed EPOT 49.6, measured EPOT 50.4, in 1977 resp. 36.8 and 36.3 cm. For Yarnton Mead, however, the difference is not negligible. In 1985 computed EPOT 37.3, measured 50.7, in 1986 resp. 44.3 and 55.5 cm. Differences between the 'measured' and MUST calculated potential evapotranspiration, figures are to be expected for difference equations have been used in their computation. However, the difference in both years for Yarnton Mead in particularly large and is to be investigated.

6.2 RESULTS OF THE MODEL SIMULATIONS WITH HUPSEL DATA

Table 7 shows the potential and actual evapotranspiration for the 7 different Hupsel profiles as computed by the MUST model (with a timestep of 7 days). The difference in potential evapotranspiration for different profiles for the same year is a consequence of the land use.

TABLE 7 Computed cumulative potential and actual evapotranspiration (cm) for 7 different profiles in the Hupsel area for 1976 and 1977. Also shown are soil type; land use and range of the groundwater table (cm below soil surface).

	Soil type	Land Use	Range ground-water table	1.4/1.10 1976		1.4/1.10 1977	
				EPOT	EACT	EPOT	EACT
Brom	Typic Haplaquod	Maize	80-213	44.0	33.3	31.4	31.4
Assink test site	Typic Haplaquod	Grass	50-179	49.6	37.0	36.8	36.8
Lensink	Typic Haplaquept 2nd type	Maize	167-280	44.0	30.5	31.4	31.2
Assink farm land	Typic Haplaquod	Maize	84-228	44.0	29.8	31.4	31.4
Ten Barge	Typic Haplaquod	Grass	42-143	49.6	45.9	36.8	36.8
Schuurmans	Typic Haplaquept 1st type	Grass	72-193	49.6	31.6	36.8	36.8
Faaks	Typic Haplaquept 1st type	Grass	82-193	49.6	29.2	39.8	36.2

All the profiles have a reduction in evapotranspiration in the dry year 1976 and, except profile Faaks, no reduction in the 'normal' year 1977. The reduction in evapotranspiration is greater for the profiles with land use maize than for the profiles with land use grass. There is no great difference in behaviour between the different soil types. Ten Barge, 1976, has almost no reduction in evapotranspiration because it is situated in a lower part of the area with a high groundwater table.

The results of the simulation for the profile Assink test site with a timestep of 1 day, is shown in Table 8. The land use is grass. There is almost no reduction in evapotranspiration in the average years 1977-1982.

TABLE 8 Computed cumulative potential and actual evapotranspiration for the profile Assink test site.

	EPOT	EACT
25.2/31.12 1976	57.1	42.4
1.1/31.12 1977	47.9	47.8
1.1/31.12 1978	48.8	48.7
1.1/31.12 1979	50.0	50.0
1.1/31.12 1980	54.6	53.0
1.1/31.12 1981	51.9	51.9
1.1/30.12 1982	55.7	48.9

The measured actual evapotranspiration for the profile Assink test site is 33.1 cm for 1976 (Commissie voor hydrologisch Onderzoek TNO, 1985). MUST computes values of 35.3 (timestep 1 day, computed EPOT), 34.7 (timestep 1 day, EPOT given, PFA = 2.7) or 37.0 (timestep 7 days, computed EPOT). These values are all too high.

6.3 RESULTS OF THE MODEL SIMULATION WITH YARNTON MEAD DATA

Table 9 shows the results of the runs made with MUST for the Yarnton Mead profile with 4 different sets of soil physical input data and the water table lowered till a certain depth below soil surface for the whole period.

TABLE 9 Computed cumulative potential and actual evapotranspiration (cm) for the Yarnton Mead profile. Period of simulation : 2.4/28.10 1985.

Depth of water table below soil surface (cm)	EPOT	Set 2 EACT	Set 3 EACT	Set 4 EACT	Set 5 EACT
80	37.3	37.3	36.5	37.0	36.3
100	37.3	37.3	36.1	36.6	35.8
120	37.3	37.3	35.8	36.2	35.3
140	37.3	37.3	35.4	36.1	35.0
160	37.3	37.3	35.3		
180	37.3	37.3	35.1		
200	37.3	37.3	35.0		
250	37.3	37.3	34.6		

SET 2 Measured soil moisture content - conductivities computed by Marshall's method.

SET 3 : Stiboka data 1

SET 4 Stiboka data 2

SET 5 : Stiboka data 3.

Lowering of the watertable has only a very small effect on the evapotranspiration for Yarnton Mead.

The differences in actual evapotranspiration between the simulations with Stiboka data 1 and Stiboka data 2 show the influence of the less conductive layer (012) in Stiboka data 1. The calculated EACT for the simulations with Stiboka data 1 are lower than those calculated with Stiboka data 2.

The differences in EACT between the simulations with Stiboka data 2 and Stiboka data 3 show the effect of the lower layer. Soil moisture content and hydraulic conductivity of the lower layer in Stiboka data 3 are lower than soil moisture content and hydraulic conductivity of the lower layer in Stiboka data 2. As a consequence the actual evapotranspiration is less.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The following conclusions can be drawn from this study:

- changing the timestep from 1 to 7 days has only a small effect on the computed actual evapotranspiration. The difference found was less than 5%.

  The effect of a change in root zone depth as small as 5 cm can be considerable, but depends on the type of soil and the meteorological circumstances. This conclusion is only valid when the land use is grass, because no simulations have been made with another land use.

  It seems that values given for the hydraulic conductivity of a subsoil layer do not have to be very exact, as long as the order of magnitude is correct. There is little to be gained from using many different subsoil layers when there are only small differences in hydraulic conductivity and soil moisture content values between them.

- The effect of a change of the parameter PFA in the evapotranspiration reduction relationship. Simulations with the model, with values for PFA of 2.4, 2.7 and 3.0, show that the computed cumulative actual evapotranspiration values differ less than 5%, while there is no shift in the evapotranspiration reduction through the period.

- Potential evapotranspiration values computed by MUST show a very good resemblance with measured potenital evapotranspiration values for the Assink test site profile. The great difference between 'measured' and MUST calculated potential evapotranspiration values for Yarnton Mead is to be investigated.

- The actual evapotranspiration values computed by MUST seem to be too high (as far as this is allowed to be concluded from <u>one</u> simulation, Assink test site 1976).

- Runs that have been made with the MUST model for the Hupsel profiles show that there is no great difference in behaviour for the different soil types. These soils are Typic Haplaquod and Typic Haplaquept.

- Simulations done for the Yarnton Mead profile show that lowering the groundwater table to 250 cm below soil surface causes almost no reduction in evapotranspiration. These simulations have been done for the wet years 1985 and 1986. It should be investigated whether this conclusion is still valid for a dry year.

In theory you can give any of the following 3 types of lower boundary conditions as input data for the MUST model:

1. the lower boundary flux is a function of the water table depth.
2. The lower boundary flux is given.
3. The water table depth is given.

In practice one can run MUST with lower boundary condition 3 because of the difficulties in measuring the lower boundary flux and in finding a suitable flux-level relationship. This means that MUST cannot be used for predictions of the groundwater table.

RECOMMENDATIONS:

In this study the focus has been, for the soil physical input data, on the importance of the hydraulic conductivity values for the results. It may be worth having a looking at the soil water characteristic data too.

- MUST contains sets of standard data. In one of them crop lengths are given in relation to the number of the day in the year. The length given for grass is 0.05/0.10 m, but the length of the grass in Yarnton Mead is 30 to 40 cm. It will be good to see if a change in the standard set of data to a more realistic value of the grass length for Yarnton Mead will make a great difference.
- The effect of a change in root zone depth has only been researched with land use grass. Some simulations should be done with another land use.

- At the moment the height of wind measurement is a value in a standard set of data for MUST. I think this value should be given as an input datum in order to prevent running MUST with a wrong height of wind measurement.

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APPENDIX 1

An example of the lower boundary solution.

The model for the lower boundary does not consider flow in the upper part of the subsoil. Consider, for example, the initial moisture profile and corresponding water table at a depth of 85 cm below the upper boundary of the subsoil in Figure 2a (broken line). The situation is followed by a time increment Δt = 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 inital curve yields the soil moisture distribution as shown in Fig. A1.

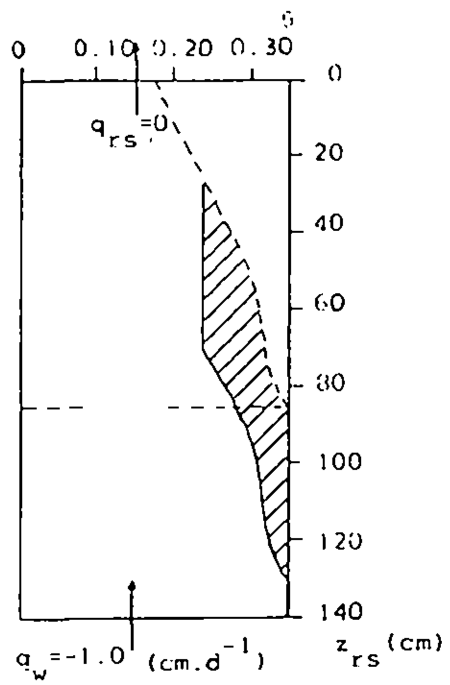


Fig.A1 Moisture profile q=-1.0 cm.d^{-1} superimposed on the initial equilibrium soil moisture distribution (broken line), where the shaded area equals the saturation deficit S_p of the percolation profile (S_p = 5cm)

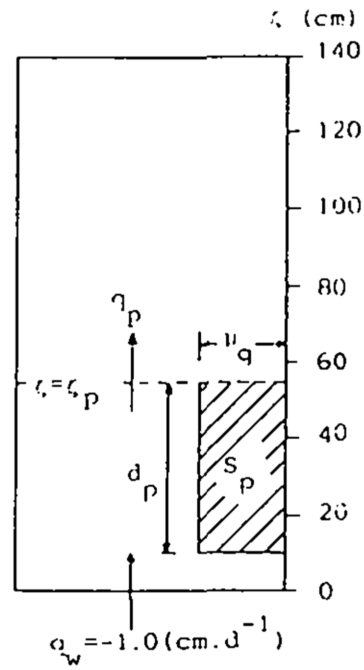


Fig.A2 Schematization of the percolation profile used for the lower boundary solution

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 $d_p = S_p/\mu_q$.

APPENDIX 2

```
C-------------------------------------------------------------------
C       PROGRAM       INTRO - TO SET INPUT DATA FOR MUST IN THE RIGHT FORMAT
C                     ON THE RIGHT PLACE
C       INTERFACE     TERMINAL , MUST INPUT AND MUST SATDAT
C       DATE        : JUNE 18TH 1987
C       AUTHOR      : ARJAN NASS
C-----------------------------------

      INTEGER COUNT
      CHARACTER TITEL*80, TEXT*30, ANSWER*1
      DIMENSION LTYP(9), LDEPTH(9), HYS(25), NSS(25), LU(25), WN(25)
      DIMENSION ETI(25), ETIP(25), GWN(25), QRSN(25), QWREL(3,25)
      DIMENSION C(11,14), TH(11,14)

      WRITE (5,10)
   10 FORMAT ('GIVE THE TITEL')
      READ (5,'(A80)') TITEL
      WRITE (7,20) TITEL
   20 FORMAT(A80)
   30 WRITE (5,40)
   40 FORMAT ('THERE ARE A FEW POSSIBILITIES FOR THE NEXT INPUT LINE.'/
     +'IF IUPP = 1 AND YOU GIVE VALUES FOR IRRIGATION THEN TYPE 1'/
     +'IF IUPP = 1 AND YOU GIVE NO VALUES FOR IRRIGATION THEN TYPE 2'/
     +'IF IUPP = 2 AND YOU GIVE A VALUE FOR PFA THEN TYPE 3 '/
     +'IF IUPP = 2 AND YOU GIVE NO VALUE FOR PFA THEN TYPE 4')
      I = 0
      READ (5,*) I
      IF (I.EQ.1) THEN
          WRITE (5,50)
   50     FORMAT ('GIVE VALUES FOR IUPP,ILOW,K1,DT,NTOT,NDTOT,NSTART,',
     +            'IYEAR,'/'GIRR,CDTIRR,CDFIRR,CPFIRR')
          READ (5,*) IUPP,ILOW,K1,DT,NTOT,NDTOT,NSTART,IYEAR,GIRR,
                     CDTIRR,CDFIRR,CPFIRR
          WRITE (7,60) IUPP,ILOW,K1,DT,NTOT,NDTOT,NSTART,IYEAR,GIRR,
     +                 CDTIRR,CDFIRR,CPFIRR
   60     FORMAT (3I6,F6.2,4I6,6X,4F6.2)
      ELSE IF (I.EQ.2) THEN
          WRITE (5,70)
   70     FORMAT ('GIVE VALUES FOR IUPP,ILOW,K1,DT,NTOT,NDTOT,NSTART,',
     +            'IYEAR')
          READ (5,*) IUPP,ILOW,K1,DT,NTOT,NDTOT,NSTART,IYEAR
          WRITE (7,80) IUPP,ILOW,K1,DT,NTOT,NDTOT,NSTART,IYEAR
   80     FORMAT (3I6,F6.2,4I6)
      ELSE IF (I.EQ.3) THEN
          WRITE (5,90)
   90     FORMAT ('GIVE THE VALUES FOR IUPP,ILOW,K1,DT,NTOT,NDTOT,PFA')
          READ (5,*) IUPP,ILOW,K1,DT,NTOT,NDTOT,PFA
          WRITE (7,100) IUPP,ILOW,K1,DT,NTOT,NDTOT,PFA
  100     FORMAT (3I6,F6.2,2I6,12X,F6.2)
      ELSE IF (I.EQ.4) THEN
          WRITE (5,110)
  110     FORMAT ('GIVE THE VALUES FOR IUPP,ILOW,K1,DT,NTOT,NDTOT')
```

Appendix 2 (Contd.)

```
          READ (5,*) IUPP,ILOW,K1,DT,NIOT,NDTOT
          WRITE (7,120) IUPP,ILOW,K1,DT,NIOT,NDTOT
120       FORMAT (3I6,F6.2,2I6)
      ELSE
          WRITE (5,130)
130       FORMAT ('YOU TYPED A WRONG NUMBER!')
          GO TO 30
      END IF

      WRITE (5,140)
140   FORMAT ('NOW THE DATA FOR THE SUBSOIL MUST BE GIVEN.'/,
     +'THIS HAS TO BE REPEATED FOR EACH DIFFERENT SUBSOIL.'/,
     +'TYPE FIRST THE NUMBER OF DIFFERENT SUBSOILS. THE MAXIMUM = 10')
      J = 0
      READ (5,*) J
      IF (J.GT.10) THEN
          WRITE (5,150)
150       FORMAT ('THE NUMBER YOU TYPED IS GREATER THEN 10. TRY AGAIN')
          READ (5,*) J
      END IF
      WRITE (5,160)
160   FORMAT ('IF YOU WANT THE SATURATION DEFICIT CURVES TO BE ',
     +        'COMPUTED SEPERATELY,'/'YOU MUST GIVE A VALUE FOR NSUBS.'/
     +        'IF THIS IS THE CASE AND THE NUMBER OF SUBSOILS IS ',
     +        'GREATER THEN 1'/'EACH NEW VALUE FOR NSUBS HAS TO BE 1 ',
     +        'GREATER THEN ITS PRECESSOR'/)
      DO 430, NCOUNT = 1,J
      WRITE (5,165)
165   FORMAT ('THERE ARE A FEW POSSIBILITIES FOR THE NEXT INPUT LINE.'/
     +'YOU DON''T HAVE TO GIVE A VALUE FOR NSUBS,AB(K,1) AND AB(K,2).'/
     +'IF YOU WANT TO GIVE A VALUE FOR THESE PARAMETERS TYPE 1'/
     +'IF YOU WANT TO GIVE A VALUE FOR NSUBS BUT NOT FOR AB(K) TYPE 2'/
     +'IF YOU DON''T WANT TO GIVE VALUES FOR THESE PARAMETERS TYPE 3')
      K = 0
      READ (5,*) K
      IF (K.EQ.1) THEN
          WRITE (5,170)
170       FORMAT ('IF YOU WANT THE SATURATION DEFICIT CURVES TO BE ',
     +            'COMPUTED SEPERATELY,'/'YOU MUST GIVE A POSITIVE ',
     +            'VALUE FOR NSUBS'/'IF THE NUMBER OF SUBSOILS IS ',
     +            'GREATER THEN 1 EACH NEW VALUE FOR NSUBS HAS TO BE 1
     +            'GREATER'/'THEN ITS PRECESSOR'/
     +            'GIVE THE VALUES FOR NSUBS,AB(K,1),AB(K,2) ')
          READ (5,*) NSUBS,AB1,AB2
          WRITE (5,180)
180       FORMAT ('TYPE THE NAME OF THE SUBSOIL')
          READ (5,'(A56)') TEXT
          WRITE (7,190) NSUBS,AB1,AB2,TEXT
190       FORMAT (I6,2F8.3,2X,A56)
      ELSE IF (K.EQ.2) THEN
          WRITE (5,200)
200       FORMAT ('GIVE THE VALUE FOR NSUBS ')
          READ (5,*) NSUBS
          WRITE (5,210)
210       FORMAT ('TYPE THE NAME OF THE SUBSOIL')
```

Appendix 2 (Contd.)

```
          READ (5,'(A56)') TEXT
          WRITE (7,220) NSUBS,TEXT
220       FORMAT (I6,13X,A56)
      ELSE
          WRITE (5,230)
230       FORMAT ('TYPE THE NAME OF THE SUBSOIL')
          READ (5,'(A56)') TEXT
          WRITE (7,240) TEXT
240       FORMAT (24X,A56)
      END IF
C------------------------------------------------------------------------
C     THE NEXT NINE LINES ARE FOR A SATURATION DEFICITE DATA FILE
C     ALL DATA WRITTEN TO FILE DEVICE 8 IS FOR THIS SATDEF DATA FILE
C------------------------------------------------------------------------

      IF ((NSUBS.GT.0) .AND. (NCOUNT.EQ.1)) THEN
          WRITE (8,20) TITEL
          WRITE (8,'(I18)') 2
      END IF
      IF ((NSUBS.GT.0) .AND. (K.EQ.1)) THEN
          WRITE (8,190) NSUBS,AB1,AB2,TEXT
      ELSE IF ((NSUBS.GT.0) .AND. (K.GT.1)) THEN
          WRITE (8,220) NSUBS,TEXT
      END IF

      ILL = 1
      L = 0
  250 L = L + 1
      IF (L.GT.11) THEN
          WRITE (5,260)
260       FORMAT ('YOU HAVE DEFINED THE MAXIMUM NUMBER OF LAYERS (11)'
          GO TO 430
      END IF
      IF (ILL.EQ.0) GO TO 320
  270 WRITE (5,280)
  280 FORMAT ('GIVE THE SOIL HYDRAULIC CONDUCTIVITY VALUES FOR THE ',
     +          'SUBSOIL')
      READ (5,*) (C(L,I),I = 2,14)
      DO 290 I = 3,14
      IF (C(L,I).GE.C(L,I-1)) GO TO 380
  290 CONTINUE
      IF (C(L,14).LT.1.E-40) GO TO 380
      WRITE (7,300) (C(L,I),I = 2,8)
      IF (NSUBS.GT.0) WRITE (8,300) (C(L,I),I = 2,8)
  300 FORMAT (7G10.3)
      WRITE (7,310) (C(L,I),I = 9,14)
      IF (NSUBS.GT.0) WRITE (8,310) (C(L,I),I = 9,14)
  310 FORMAT (6G10.3)
  320 WRITE (5,330)
  330 FORMAT ('GIVE THE SOIL MOISTURE CONTENT VALUES FOR THE SUBSOIL')
      READ (5,*) (TH(L,I),I = 2,14)
      DO 340 I = 3,14
      IF (TH(L,I).GE.TH(L,I-1)) GO TO 400
  340 CONTINUE
```

Appendix 2 (Contd.)

```
      WRITE (7,350) (TH(L,I),I = 2,14)
      IF (NSUBS.GT.0) WRITE (8,350) (TH(L,I),I = 2,14)
  350 FORMAT (13F6.3)
      WRITE (5,360)
  360 FORMAT ('GIVE THE VALUES FOR LAYER AND ILL.'/
     +        'LOOK OUT! LAYER IS THE DEPTH BELOW THE TOP OF THE SUBSOIL')
      READ (5,*) LAYER,ILL
      WRITE (7,370) LAYER,ILL
      IF (NSUBS.GT.0) WRITE (8,370) LAYER,ILL
  370 FORMAT (2I6)
      IF (LAYER.EQ.0) GO TO 420
      GO TO 250
  380 WRITE(5,390)
  390 FORMAT (/'ERROR INPUT LINE WITH SOIL HYDRAULIC CONDUCTIVITY DATA',
     +        ' SUBSOIL'/'TRY AGAIN')
      GO TO 270
  400 WRITE (5,410)
  410 FORMAT (/'ERROR INPUT LINE WITH SOIL MOISTURE CONTENT DATA ',
     +        'SUBSOIL'/'TRY AGAIN')
      GO TO 320
  420 CONTINUE
  430 CONTINUE
      WRITE (7,440)
      IF (NSUBS.GT.0) WRITE (8,440)
  440 FORMAT ('999999')

      I = 0
      L = 0
  450 L = L +1
      WRITE (5,460)
  460 FORMAT ('NOW THE DATA FOR THE ROOT ZONE MUST BE GIVEN')
  470 WRITE (5,480)
  480 FORMAT ('GIVE THE SOIL MOISTURE CONTENT VALUES FOR THE ROOT ZONE')
      READ (5,*) (TH(L,I),I = 2,14)
      DO 490 I = 2,13
      IF (TH(L,I).LT.TH(L,I+1)) GO TO 550
  490 CONTINUE
      WRITE (7,500) (TH(L,I),I = 2,14)
  500 FORMAT (13F6.3)
      WRITE (5,510)
  510 FORMAT ('GIVE THE NAME OF THE LAYER')
      READ (5,'(A28)') TEXT
      WRITE (7,520) TEXT
  520 FORMAT (A28)
      WRITE (5,530)
  530 FORMAT ('IF THERE ARE SOIL MOISTURE CONTENT VALUES FOR AN OTHER ',
     +        'ROOT ZONE'/'TYPE YES ELSE TYPE NO')
      READ (5,'(A)') ANSWER
      IF (ANSWER.EQ.'Y') THEN
          GO TO 470
      ELSE
          WRITE (7,540)
  540     FORMAT ('999999')
          GO TO 570
      END IF
```

Appendix 2 (Contd)

```
550 WRITE (5,560)
560 FORMAT (/'ERROR INPUT LINE WITH SOIL MOISTURE CONTENT DATA ROOT
   +            'ZONE'/'TRY AGAIN')
    GO TO 470

570 CONTINUE
    NSUBS = NSUBS - (J-1)
    DO 680, ND = 1,NDTOT
    I = 0
    DO 580 I = 1,9
    LTYP(I) = 0
580 LDEPTH(I) = 0
    IF (ILOW.EQ.1) THEN
        WRITE (5,590)
590     FORMAT ('GIVE THE VALUES FOR LTYP(1),LDEPTH(1),HYS(ND),',
   +            'NSS(ND),LU(ND),WN(ND),ETI(ND),'/
   +            'QWN(ND),QWREL(1,ND),QWREL(2,ND),QWREL(3,ND)')
        IF (J.GT.1) THEN
            WRITE (5,600) NSUBS
600         FORMAT ('THE NUMBER OF THE SUBSOIL FOR WHICH THESE DATA '
   +                'MUST BE GIVEN IS ',I2)
            NSUBS = NSUBS + 1
        END IF
        READ (5,*) LTYP(1),LDEPTH(1),HYS(ND),NSS(ND),LU(ND),WN(ND),
                   ETI(ND),QWN(ND),(QWREL(I,ND),I=1,3)
        WRITE (7,610) LTYP(1),LDEPTH(1),HYS(ND),NSS(ND),LU(ND),WN(ND),
   +                  ETI(ND),QWN(ND),(QWREL(I,ND),I=1,3)
610     FORMAT (2I6,F6.2,2I6,F6.1,5F8.3)
    ELSE IF (ILOW.GT.1) THEN
        WRITE (5,620)
620     FORMAT ('GIVE THE VALUES FOR LTYP(1),LDEPTH(1),HYS(ND),',
   +            'NSS(ND),LU(ND),WN(ND),ETI(ND),'/'QWN(ND)')
        IF (J.GT.1) THEN
            WRITE (5,630) NSUBS
630         FORMAT ('THE NUMBER OF THE SUBSOIL FOR WHICH THESE DATA ',
   +                'MUST BE GIVEN IS ',I2)
            NSUBS = NSUBS + 1
        END IF
        READ (5,*) LTYP(1),LDEPTH(1),HYS(ND),NSS(ND),LU(ND),WN(ND),
                   ETI(ND),QWN(ND)
        WRITE (7,640) LTYP(1),LDEPTH(1),HYS(ND),NSS(ND),LU(ND),WN(ND)
   +                  ETI(ND),QWN(ND)
640     FORMAT (2I6,F6.2,2I6,F6.1,2F8.3)
    END IF

    IF (LTYP(1).EQ.0) THEN
        WRITE (5,650)
650     FORMAT ('THE ROOT ZONE IS HETEROGENUOUS.'/'YOU HAVE TO ',
   +    'SPECIFY THE LAYERS AND DEPTH OF THE LAYERS OF THE ROOT ZONE',
   +    'GIVE FIRST THE TOTAL NUMBER OF LAYERS. THE MAXIMUM = 9')
        M = 0
        READ (5,*) M
        WRITE (5,660)
660     FORMAT('GIVE THE VALUES FOR LTYP(I) AND LDEPTH(I)')
        READ (5,*) (LTYP(I),LDEPTH(I), I = 1,M)
```

Appendix 2 (contd.)

```
          IF (M.LE.6) THEN
               WRITE (7,670) (LTYP(I),LDEPTH(I), I = 1,M)
          ELSE
               WRITE (7,670) (LTYP(I),LDEPTH(I), I = 1,6)
               WRITE (7,670) (LTYP(I),LDEPTH(I), I = 7,M)
          END IF
670       FORMAT (12I6)
      END IF
680   CONTINUE

      WRITE (5,685)
685   FORMAT ('SOMETIMES THE METEOROLOGICAL DATA ARE READ FROM AN ',
     +        'OTHER FILE'/'IF THIS IS THE CASE TYPE YES, ELSE TYPE NO')
      READ (5,'(A)') ANSWER
      IF (ANSWER.EQ.'Y') GO TO 805

      IF (IUPP.EQ.1) THEN
          WRITE (5,690)
690       FORMAT ('A VALUE FOR RNET IS NOT REQUIRED, BUT IF GIVEN'/
     +    'THIS VALUE IS USED FOR THE CALCULATION OF THE '/
     +    'EVAPOTRANPIRATION,BUT NOT FOR THE CALCULATION OF EPEN.'/
     +    'THE LATTER MAY BE ACCOMPLISHED BY ENTERING A NEGATIVE ',
     +    'VALUE INTO FRSUN.'/
     +    'IF YOU GIVE A VALUE FOR RNET TYPE YES, ELSE TYPE NO')
           READ (5,'(A)') ANSWER
      END IF
      COUNT = 0
      DO 800, COUNT = 1,NTOT
          IF (IUPP.EQ.1) THEN
               IF (ANSWER.EQ.'Y') THEN
                 WRITE (5,700)
700              FORMAT ('GIVE THE VALUES FOR U,FRSUN,RH,TEMP,RAIN,RNET')
                 READ (5,*) U,FRSUN,RH,TEMP,RAIN,RNET
                 WRITE (7,710) U,FRSUN,RH,TEMP,RAIN,RNET
710              FORMAT (F6.1,2F6.3,F6.1,F6.2,F6.1)
               ELSE
                 WRITE (5,720)
720              FORMAT ('GIVE THE VALUES FOR U,FRSUN,RH,TEMP,RAIN')
                 READ (5,*) U,FRSUN,RH,TEMP,RAIN
                 WRITE (7,730) U,FRSUN,RH,TEMP,RAIN
730              FORMAT (F6.1,2F6.3,F6.1,F6.2)
               END IF
          ELSE IF (IUPP.EQ.2) THEN
               WRITE (5,740)
740            FORMAT ('GIVE THE VALUES FOR RAIN AND ETIP, NDTOT TIME')
               READ (5,*) RAIN,(ETIP(ND), ND = 1,NDTOT)
               WRITE (7,750) RAIN,(ETIP(ND), ND = 1,NDTOT)
750            FORMAT (13F6.3)
          END IF
          IF (ILOW.EQ.2) THEN
               WRITE (5,760)
760            FORMAT('GIVE THE VALUE FOR QWN(ND), NDTOT TIME')
               READ (5,*) (QWN(ND), ND = 1,NDTOT)
               WRITE (7,770) (QWN(ND), ND = 1,NDTOT)
770            FORMAT (13F6.3)
```

Appendix 2 (Contd.)

```
          ELSE IF (ILOW.EQ.3) THEN
              WRITE (5,780)
 780          FORMAT ('GIVE THE VALUES FOR WN(ND),NOTOT TIME')
              READ (5,*) (QRSN(ND), ND = 1,NOTOT)
              WRITE (7,790) (QRSN(ND), ND = 1,NOTOT)
 790          FORMAT (13F6.1)
          END IF
 800 CONTINUE
 805 WRITE (5,810)
 810 FORMAT (//'END OF DATA INPUT FOR THE PROGRAM MUST'//)
     WRITE (5,820)
 820 FORMAT('MUST GIVES THE CUMULATIVE VALUES OF THE RAIN, IRRIGATION'/
    +      'EVAPOTRANSPIRATION AND INTERCEPTION AFTER EACH TIMESTEP'/
    +      'IF YOU WANT TO START COMPUTING THESE CUMULATIVE VALUES ',
    +      'AT A CERTAIN TIMESTEP,'/'YOU MUST TYPE -1 IN THE FIRST ',
    +      'POSITIONS OF THE INPUT LINE BEFORE THIS TIMESTEP'/
    +      'YOU MUST DO THIS IN THE OUTPUT FILE OF THIS PROGRAM')
     WRITE (5,830)
 830 FORMAT (//'                    WARNING              '/
    +      'CHECK IF THE HEIGHT OF WIND MEASUREMENT IN THE ',
    +      'PROGRAM MUST FORTRAN'/'IS SET TO THE CORRECT VALUE')
     END
```

APPENDIX 3

... Input Data ... Model for Unsaturated Flow above a Shallow Water Table MUST

TEXT

A80

IUPP	ILOW	KI	DT	NTOT	NDTOT	NSTART	IYEAR	PPA	CIRR	CDTIRR	CDFIRR	CPFIRR
I 6	I 6	I 6	F 6.2	I 6	I 6	I 6	I 6	F 6.2	F 6.2	F 6.2	F 6.2	F 6.2

REPEAT FOR OTHER SUBSOILS:

NSUBS	AB(X,1)	AB(X,2)
I 6	F 8.3	F 8.3

TEXT

A 56

REPEAT IF LAYER > 0 AND ILL > 0:

C(L,2)	C(L,3)	C(L,4)	C(L,5)	C(L,6)	C(L,7)	C(L,8)
F 10.3	F 10.3	F 10.3	F 10.3	F 10.3	F 10.3	F 10.3

C(L,9)	C(L,10)	C(L,11)	C(L,12)	C(L,13)	C(L,14)
F 10.3	F 10.3	F 10.3	F 10.3	F 10.3	F 10.3

REPEAT IF LAYER > 3:

TH(L,2)	TH(L,3)	TH(L,4)	TH(L,5)	TH(L,6)	TH(L,7)	TH(L,8)	TH(L,9)	TH(L,10)	TH(L,11)	TH(L,12)	TH(L,13)	TH(L,14)
F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3

LAYER	ILL
I 6	I 6

END OF SUBSOIL DATA

999999

I 6

REPEAT FOR OTHER SOIL MOISTURE CHAR. OF THE ROOT ZONE:

TH(L,2)	TH(L,3)	TH(L,4)	TH(L,5)	TH(L,6)	TH(L,7)	TH(L,8)	TH(L,9)	TH(L,10)	TH(L,11)	TH(L,12)	TH(L,13)	TH(L,14)
F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3	F 6.3

TEXT

A 28

END OF ROOT ZONE DATA

999999

I 6

REPEAT NDTOT TIMES:

LTYP(1)	LDEPTH(1)	HYS	NSS	LU	WN	ETI	QWN	QWREL(1,)	QWREL(2,)	QWREL(3,)
I 6	I 6	F 6.2	I 6	I 6	F 6.1	F 8.3	F 8.3	F 8.3 **	F 8.3 **	F 8.3 **

FOR HETEROGENEOUS ROOT ZONE ONLY:

LTYP(1) LDEPTH(1) LTYP(2) LDEPTH(2) etc maximally 9 layers, continue onto next line, if necessary

I 6 I 6 I 6 I 6

REPEAT NTOT TIMES:

ONLY FOR IUPP = 1:

U	FRSUN	RH	TEMP	RAIN	RNET
F 6.1	F 6.3	F 6.3	F 6.1	F 6.3	F 6.1

ONLY FOR IUPP = 2:

RAIN ETIP(1) ETIP(2) ETIP(3) etc · last value is ETIP(NDTOT), continue onto next lines if necessary

F 6.3 F 6.3 F 6.3 F 6.3

ONLY FOR ILOW = 2:

QWN(1) QWN(2) QWN(3) etc last value is QWN(NDTOT), continue onto next lines if necessary

F 6.3 F 6.3 F 6.3

ONLY FOR ILOW = 3:

WN(1) WN(2) WN(3) etc last value is WN(NDTOT), continue onto next lines if necessary

F 6.1 F 6.1 F 6.1

LU land use
1 grass
2 cereals
3 maize
4 potatoes
5 sugar beets
6 deciduous forest
7 coniferous forest
8 special crop

Standard series of matric pressure values (mbar, positive)

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

IUPP =
1- evapotranspiration is computed
2- potential evapotranspiration data are given

ILOW =
1- flux-level relation is specified
2- lower boundary flux is given
3- water table-depth is given

• no value required

* for IUPP = 2 no value required

** for ILOW > 1 no value required

F-Formats may be read as E-Formats

APPENDIX 4

The input data for the three examples given by De Laat, 1985,
but now in the 'new' format.

```
EXAMPLE NO.
     1       1       1 10.00      10       1      91   1971             2.00 20.00              0
     0   -0.010   -0.060   MEDIUM FINE SAND
  70.0          29.9          12.8          5.02          1.00        0.140E-01 0.110E-02
 0.420E-03 0.160E-03 0.440E-04 0.170E-04 0.630E-05 0.330E-05
 0.393 0.352 0.337 0.328 0.297 0.208 0.114 0.094 0.068 0.037 0.030 0.026 0
    50       0
 0.330 0.320 0.313 0.306 0.296 0.255 0.151 0.119 0.100 0.086 0.075 0.064
     0       0
999999
 0.500 0.427 0.410 0.392 0.354 0.284 0.206 0.168 0.131 0.092 0.074 0.061
PODZOL
999999
     1      30   0.50        1         1 110.0   -0.100   -0.100   -0.260 210.00
   2.2 0.233 0.342    3.1   0.00
   2.4 0.415 0.743    3.3   0.02
   2.5 0.475 0.679    3.9   0.22
   2.4 0.533 0.603   12.8   0.02
   2.1 0.427 0.762   16.3   0.40
   2.3 0.315 0.773   13.6   0.14
   2.3 0.479 0.722   17.2   0.00
   2.3 0.149 0.855   12.2   0.68
   2.7 0.230 0.304   13.9   0.38
   1.7 0.705 0.725   18.3   0.03

EXAMPLE NO. 2
     2       2       0 10.00      10       1                  4.20
     0   -0.010   -0.060   MEDIUM FINE SAND
  70.0          29.9          12.8          5.02          1.00        0.140E-01 0.110E-02
 0.420E-03 0.160E-03 0.440E-04 0.170E-04 0.630E-05 0.330E-05
 0.393 0.352 0.337 0.328 0.297 0.208 0.114 0.094 0.068 0.037 0.030 0.026 0.024
    50       0
 0.330 0.320 0.313 0.306 0.296 0.255 0.151 0.119 0.100 0.086 0.075 0.064 0.055
     0       0
999999
 0.500 0.427 0.410 0.392 0.354 0.284 0.206 0.168 0.131 0.092 0.074 0.062 0.05
PODZOL
999999
     1      30   0.50                   110.   -0.100   -0.100
 0.000 0.110
-0.101
 0.020 0.190
-0.084
 0.220 0.240
-0.072
 0.220 0.300
-0.063
 0.400 0.300
-0.056
 0.340 0.250
-0.052
 0.000 0.200
-0.047
 0.880 0.160
-0.113
 0.380 0.240
-0.114
 0.230 0.370
-0.093
```

Appendix 4 (Contd)

Input data for the computation of the saturation deficit curves for the third example :

```
EXAMPLE NO.

     5                         NO CLAY LOAM
  110.       48.3        21.2        8.60        1.80       0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.023
     0      0
     6                         CLAY LOAM BETWEEN 0 AND 10 CM
  1.00       0.780       0.609       0.464       0.289      0.840E-01 0.200E-02
 0.280E-03 0.110E-03 0.300E-04 0.110E-04 0.420E-05 0.220E-05
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
    10      1
  110.       48.3        21.2        8.60        1.80       0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.023
     0      0
     7                         CLAY LOAM BETWEEN 30 AND 40 CM
  110.       48.3        21.2        8.60        1.80       0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.023
    30      1
  1.00       0.780       0.609       0.464       0.289      0.840E-01 0.200E-02
 0.280E-03 0.110E-03 0.300E-04 0.110E-04 0.420E-05 0.220E-05
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
    40      1
  110.       48.3        21.2        8.60        1.80       0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
     0      0
     8                         CLAY LOAM BETWEEN 60 AND 70 CM
  110.       48.3        21.2        8.60        1.80       0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
    60      1
  1.00       0.780       0.609       0.464       0.289      0.840E-01 0.200E-02
 0.280E-03 0.110E-03 0.300E-04 0.110E-04 0.420E-05 0.220E-05
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
    70      1
  110.       48.3        21.2        8.60        1.80       0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
     0      0
999999
```

Appendix 4 (Contd)

```
EXAMPLE NO. 3
     1       3       0 30.00       9       4       1  1971
     5                          NO CLAY LOAM
  110.        48.3         21.2         8.60         1.80        0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.023
     0       0
     6                          CLAY LOAM BETWEEN 0 AND 10 CM
  1.00       0.780       0.609       0.464       0.289       0.840E-01 0.200E-02
 0.280E-03 0.110E-03 0.300E-04 0.110E-04 0.420E-05 0.220E-05
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
    10       1
  110.        48.3         21.2         8.60         1.80        0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.023
     0       0
     7                          CLAY LOAM BETWEEN 30 AND 40 CM
  110.        48.3         21.2         8.60         1.80        0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.023
    30       1
  1.00       0.780       0.609       0.464       0.289       0.840E-01 0.200E-02
 0.280E-03 0.110E-03 0.300E-04 0.110E-04 0.420E-05 0.220E-05
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
    40       1
  110.        48.3         21.2         8.60         1.80        0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
     0       0
     8                          CLAY LOAM BETWEEN 60 AND 70 CM
  110.        48.3         21.2         8.60         1.80        0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
    60       1
  1.00       0.780       0.609       0.464       0.289       0.840E-01 0.200E-02
 0.280E-03 0.110E-03 0.300E-04 0.110E-04 0.420E-05 0.220E-05
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
    70       1
  110.        48.3         21.2         8.60         1.80        0.300E-01 0.140E-02
 0.550E-03 0.210E-03 0.580E-04 0.220E-04 0.830E-05 0.430E-05
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
     0       0
999999
 0.350 0.325 0.316 0.305 0.260 0.155 0.077 0.061 0.050 0.043 0.032 0.025 0.000
MEDIUM FINE SAND
 0.445 0.429 0.424 0.421 0.415 0.411 0.385 0.366 0.344 0.342 0.286 0.265 0.255
CLAY LOAM
999999
     0      0  0.50      1      4 110.0    0.000    0.000
     2     10     1     30
     1     30  0.50      2      4 110.0    0.000    0.000
     1     30  0.50      3      4 110.0    0.000    0.000
     1     30  0.50      4      4 110.0    0.000    0.000
   3.4 0.105 0.933    1.2   0.17
 110.0 110.0 110.0 110.0
   3.6 0.179 0.873    3.5   0.12
 110.0 110.0 110.0 110.0
   3.3 0.231 0.837    2.7   0.08
 110.0 110.0 110.0 110.0
-1
   3.0 0.340 0.770    7.1   0.04
 110.0 110.0 110.0 110.0
   2.7 0.472 0.709   12.9   0.14
 110.0 110.0 110.0 110.0
   2.8 0.328 0.793   13.6   0.29
 110.0 110.0 110.0 110.0
   2.6 0.488 0.753   16.8   0.11
 110.0 110.0 110.0 110.0
   2.8 0.404 0.792   17.0   0.19
 110.0 110.0 110.0 110.0
   2.4 0.454 0.790   13.6   0.14
 110.0 110.0 110.0 110.0
```

APPENDIX 5

The soil physical input data for Yarnton Mead

The first set, Geharda's data :

```
YARNTON TEST SITE; PX-11 (0153)
     1      3      1  7.00     30              92  1985
     1
  999.       345.       147.       55.0       18.0       8.00       4.00
 0.400      0.130      0.110E-01 0.270E-02 0.750E-03 0.280E-03
 0.621 0.585 0.577 0.569 0.561 0.553 0.548 0.522 0.493 0.442 0.408 0.378 0.352
    13      1
 0.490E+04  281.       107.       35.0       9.00       5.00       0.800
 0.110      0.540E-01 0.720E-02 0.160E-02 0.680E-03 0.320E-03
 0.522 0.502 0.495 0.487 0.477 0.472 0.461 0.447 0.437 0.404 0.384 0.360 0.345
    66      1
 0.900E+04 0.110E+04  101.       36.0       11.0       3.20       0.560
 0.110      0.380E-01 0.400E-02 0.190E-02 0.150E-02 0.210E-03
 0.465 0.362 0.299 0.274 0.254 0.233 0.211 0.184 0.168 0.134 0.118 0.110 0.105
     0      0
999999
 0.875 0.785 0.757 0.738 0.714 0.670 0.585 0.470 0.303 0.265 0.252 0.246 0.243
0-10 CM
 0.760 0.727 0.710 0.694 0.673 0.634 0.560 0.448 0.297 0.280 0.246 0.238 0.234
10-20 CM
 0.621 0.585 0.577 0.569 0.561 0.553 0.548 0.522 0.493 0.442 0.408 0.378 0.352
20-30 CM
999999
     0      0  1.00      1      1   43.5    0.000    0.000
     1     10     2     20      3     30
```

The second set, measured soil moisture content and computed conductivities

```
YARNTON TEST SITE ; PX-11 (0153)
     1      3      1  7.00     30      1      92  1985
     2
 0.100E+04  90.9       3.00       1.30       0.600      0.250      0.900E-01
 0.200E-01 0.700E-03 0.220E-03 0.150E-03 0.110E-03 0.950E-04
 0.850 0.730 0.714 0.702 0.685 0.656 0.572 0.375 0.246 0.216 0.211 0.208 0.207
    13      1
 0.100E+04  19.0       9.00       5.60       3.00       1.10       0.260
 0.530E-02 0.460E-03 0.900E-04 0.280E-04 0.850E-05 0.360E-05
 0.568 0.538 0.527 0.518 0.506 0.480 0.419 0.346 0.263 0.227 0.215 0.208 0.205
    69      1
 0.900E+04 0.110E+04  101.       36.0       11.0       3.20       0.560
 0.110      0.380E-01 0.400E-02 0.190E-02 0.150E-02 0.210E-03
 0.465 0.362 0.299 0.274 0.254 0.233 0.211 0.184 0.168 0.134 0.118 0.110 0.105
     0      0
999999
 0.875 0.785 0.757 0.738 0.714 0.670 0.585 0.470 0.303 0.265 0.252 0.246 0.243
0-10 CM
 0.760 0.727 0.710 0.694 0.673 0.634 0.560 0.448 0.297 0.280 0.246 0.238 0.234
10-20 CM
 0.621 0.585 0.577 0.569 0.561 0.553 0.548 0.522 0.493 0.442 0.408 0.378 0.352
20-30 CM
999999
     0      0  1.00      1      1   43.5    0.000    0.000
     1     10     2     20      3     30
```

Appendix 5 (Contd)

The third set, Stiboka data 1

```
YARNTON TEST SITE PX-11 (0153) ; STIBOKA DATA1
     1      3      1  7.00     30      1     92   1985
     3
  63.6       0.357       0.121       0.450E-01 0.220E-01 0.590E-02 0.187E-02
 0.956E-03 0.453E-03 0.216E-03 0.841E-04 0.492E-04 0.311E-04
 0.517 0.473 0.465 0.459 0.452 0.436 0.394 0.344 0.298 0.248 0.218 0.188 0.173
    13      1
  10.8       0.232       0.134       0.440E-01 0.300E-01 0.110E-01 0.328E-02
 0.143E-02 0.532E-03 0.173E-03 0.725E-04 0.308E-04 0.186E-04
 0.492 0.480 0.475 0.470 0.464 0.452 0.411 0.366 0.313 0.262 0.231 0.202 0.184
    49      1
  61.0       0.733       0.384       0.104       0.890E-01 0.350E-01 0.820E-02
 0.281E-02 0.101E-02 0.235E-03 0.754E-04 0.152E-04 0.480E-05
 0.419 0.400 0.393 0.388 0.381 0.365 0.331 0.314 0.261 0.221 0.192 0.165 0.150
    70      1
  63.9        16.5        8.40        5.02        2.70        0.959       0.270E-02
 0.370E-03 0.523E-04 0.855E-05 0.160E-05 0.540E-06 0.100E-06
 0.381 0.355 0.340 0.327 0.303 0.198 0.100 0.073 0.058 0.047 0.039 0.034 0.030
     0      0
999999
 0.448 0.409 0.401 0.396 0.389 0.377 0.350 0.320 0.263 0.217 0.187 0.159 0.143
B10 - LIGHT CLAY
 0.517 0.473 0.465 0.459 0.452 0.436 0.394 0.344 0.298 0.248 0.218 0.188 0.173
B11 - MEDIUM HEAVY CLAY
999999
     0      0  1.00      1      1  43.5    0.000    0.000
     1     20      2     30
```

The fourth set, Stiboka data 2 :

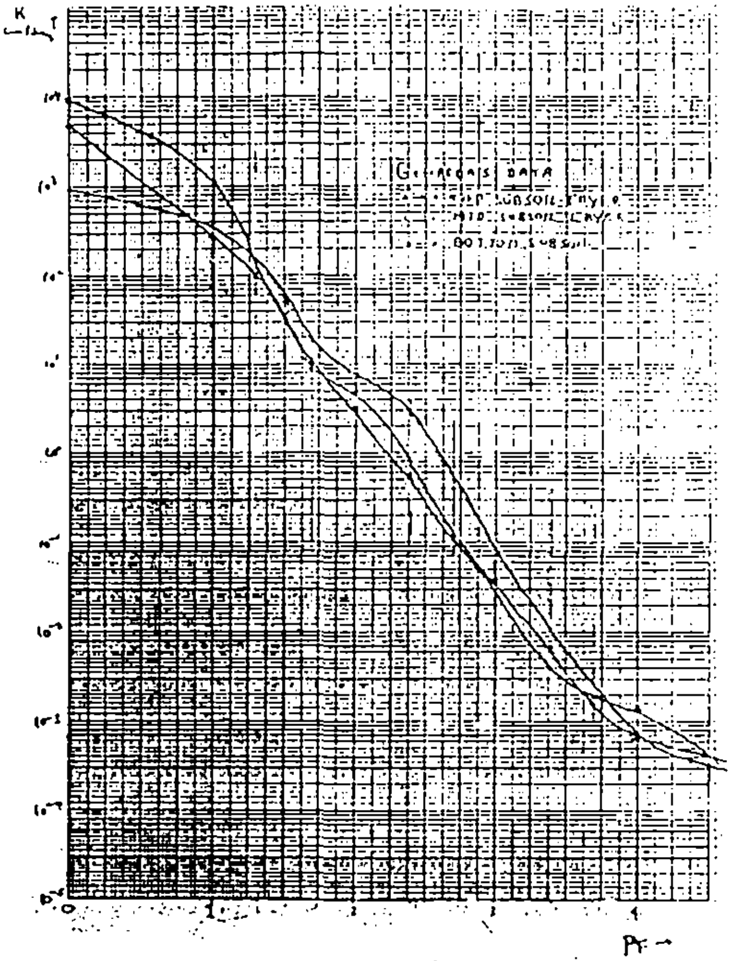
```
YARNTON TEST SITE PX-11 (0153) ; STIBOKA DATA2
     1      3      1  7.00     30      1     92   1985
     3
  63.6       0.357       0.121       0.450E-01 0.220E-01 0.590E-02 0.187E-02
 0.956E-03 0.453E-03 0.216E-03 0.841E-04 0.492E-04 0.311E-04
 0.517 0.473 0.465 0.459 0.452 0.436 0.394 0.344 0.298 0.248 0.218 0.188 0.173
    13      1
  61.0       0.733       0.384       0.104       0.890E-01 0.350E-01 0.820E-02
 0.281E-02 0.101E-02 0.235E-03 0.754E-04 0.152E-04 0.480E-05
 0.419 0.400 0.393 0.388 0.381 0.365 0.331 0.314 0.261 0.221 0.192 0.165 0.150
    70      1
  63.9        16.5        8.40        5.02        2.70        0.959       0.270E-02
 0.370E-03 0.523E-04 0.855E-05 0.160E-05 0.540E-06 0.100E-06
 0.381 0.355 0.340 0.327 0.303 0.198 0.100 0.073 0.058 0.047 0.039 0.034 0.030
     0      0
999999
 0.448 0.409 0.401 0.396 0.389 0.377 0.350 0.320 0.263 0.217 0.187 0.159 0.143
B10 - LIGHT CLAY
 0.517 0.473 0.465 0.459 0.452 0.436 0.394 0.344 0.298 0.248 0.218 0.188 0.173
B11 - MEDIUM HEAVY CLAY
999999
     0      0  1.00      1             43.5    0.000    0.000
     1     20      2     30
```

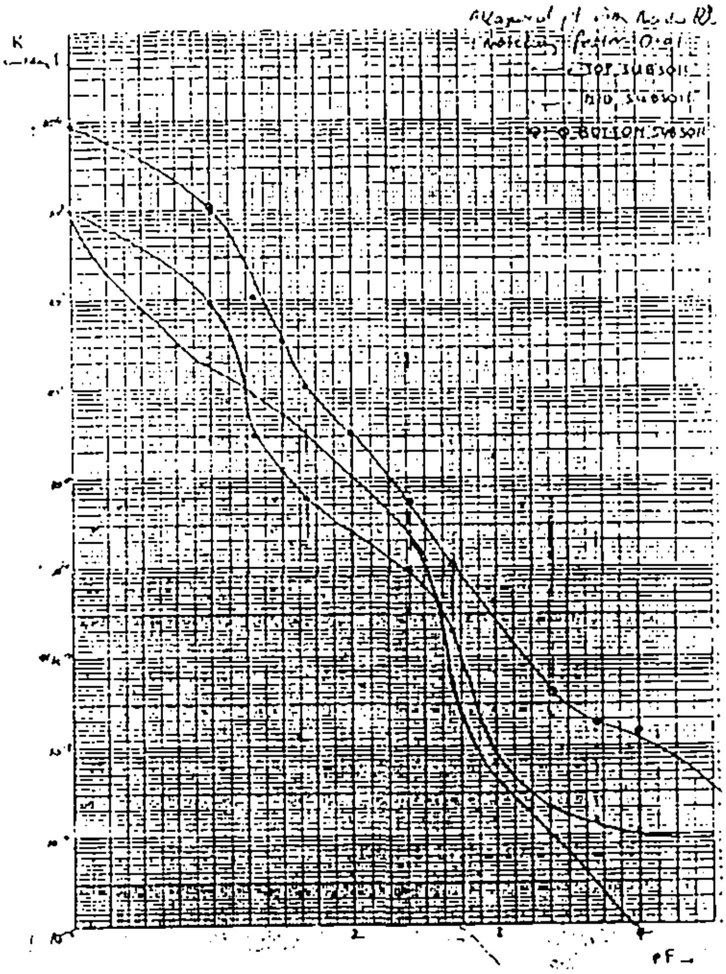
Appendix 5 (Contd.)

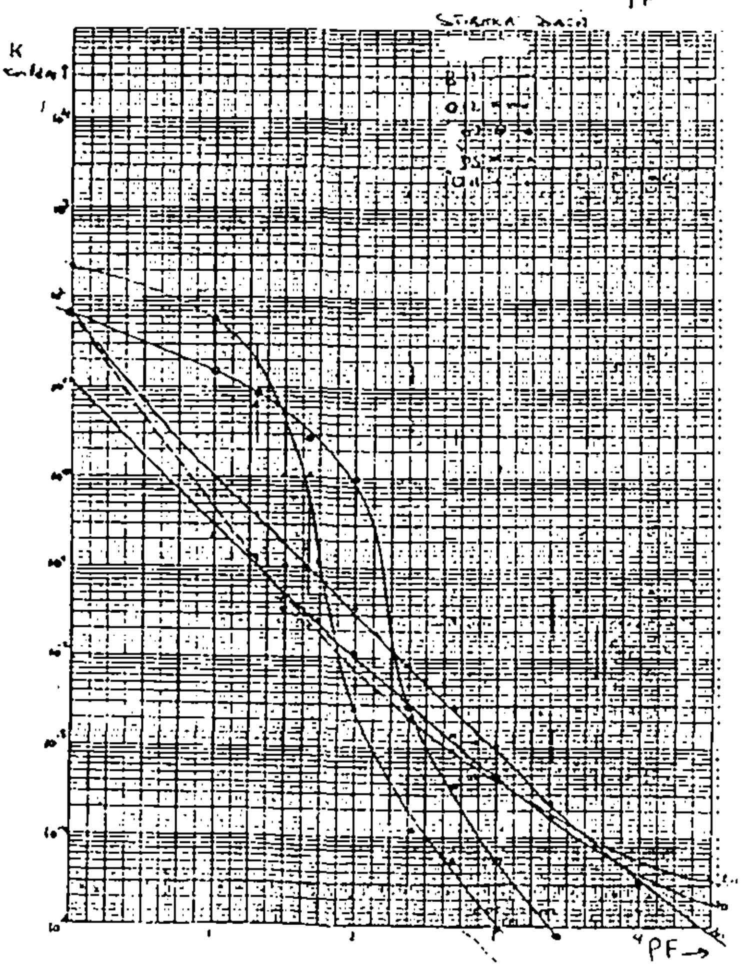
The fifth set, Stiboka data 3 :

```
YARNTON TEST SITE PX-11 (0153) ; STIBOKA DATA3
     1     3     1  7.00    30     1    92  1985
     3
  65.6      0.357      0.121      0.450E-01 0.220E-01 0.590E-02 0.187E-02
 0.956E-03 0.453E-03 0.216E-03 0.841E-04 0.492E-04 0.311E-04
 0.517 0.473 0.465 0.459 0.452 0.436 0.394 0.344 0.298 0.248 0.218 0.188 0.173
    13     1
  61.0      0.733      0.384      0.104      0.890E-01 0.350E-01 0.820E-02
 0.281E-02 0.101E-02 0.235E-03 0.754E-04 0.152E-04 0.480E-05
 0.419 0.400 0.393 0.388 0.381 0.365 0.331 0.314 0.261 0.221 0.192 0.165 0.150
    70     1
  223.      58.4       6.94       1.09       1.03      0.265E-02 0.110E-03
 0.506E-04 0.987E-05 0.100E-05 0.783E-06 0.100E-06 0.130E-07
 0.332 0.303 0.255 0.190 0.115 0.076 0.048 0.037 0.029 0.020 0.018 0.014 0.010
     0     0
999999
 0.448 0.409 0.401 0.396 0.389 0.377 0.350 0.320 0.263 0.217 0.187 0.159 0.143
B10 - LIGHT CLAY
 0.517 0.473 0.465 0.459 0.452 0.436 0.394 0.344 0.298 0.248 0.218 0.188 0.173
B11 - MEDIUM HEAVY CLAY
999999
     0     0  1.00     1          43.5    0.000    0.000
     1    20     2    30
```

APPENDIX 6 SURVEY OF THE HYDRAULIC CONDUCTIVITIES FOR THE DIFFERENT LAYERS OF THE SUBSOIL FOR YARNTON MEAD.

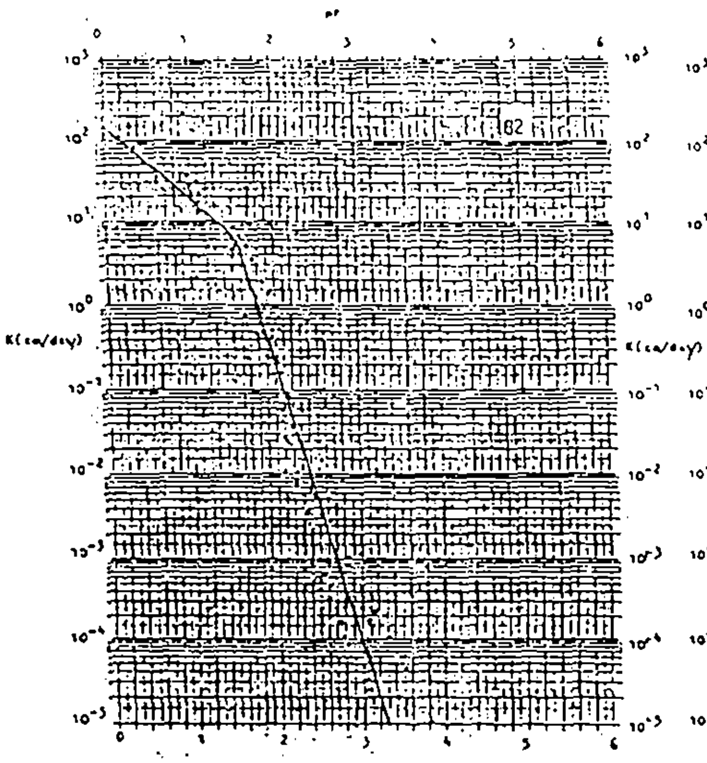


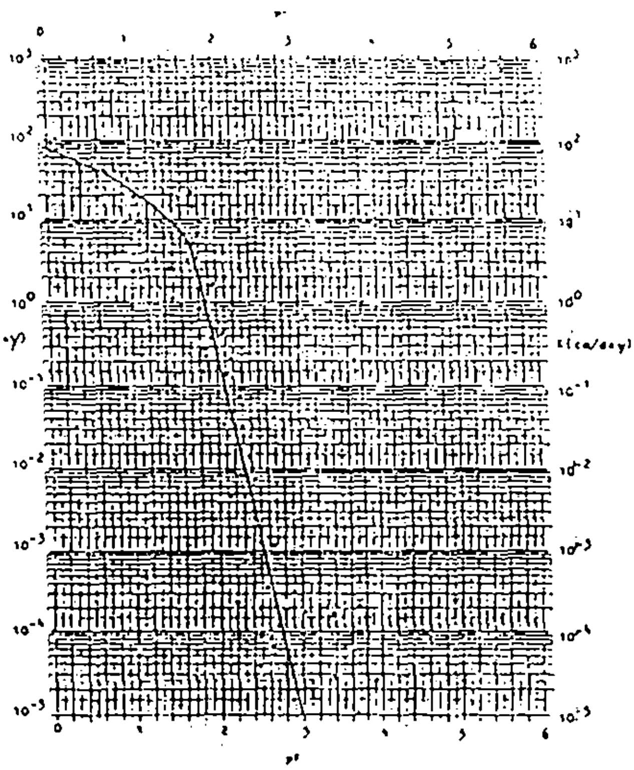


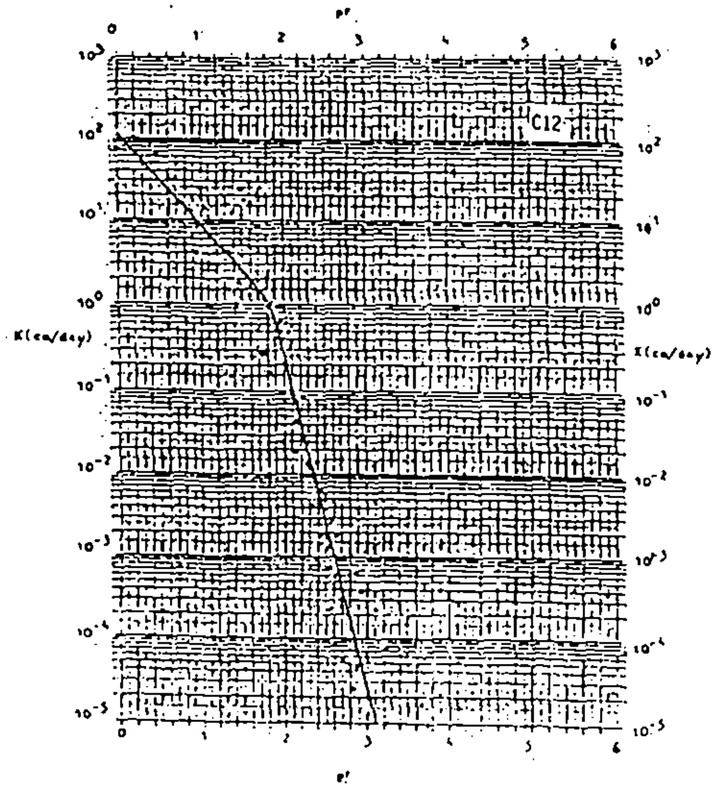


APPENDIX 7

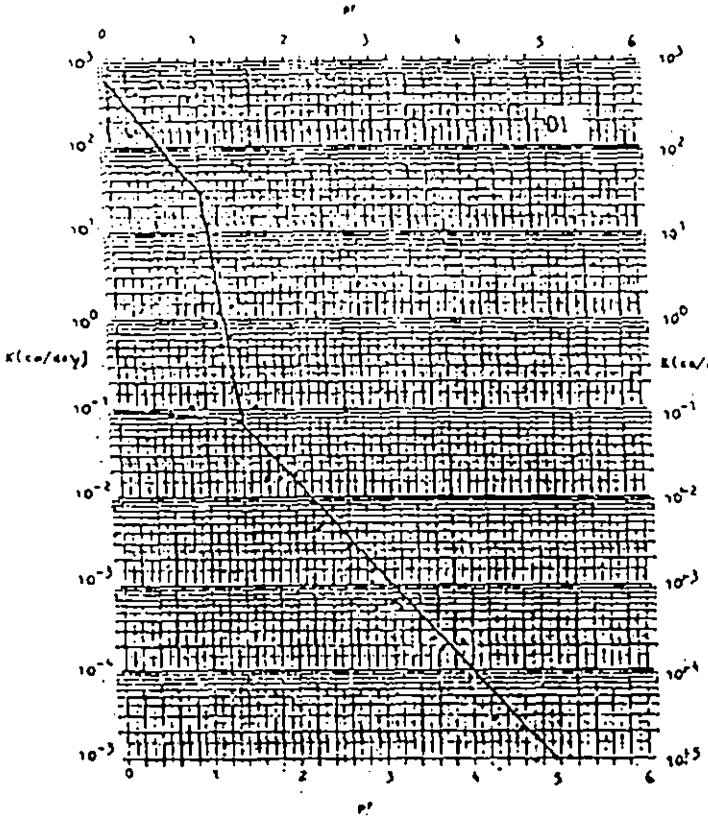
Comprehension of the measured K-h relations (datapoints) with the drawn regressionline for the horizons of the Hupsel profi

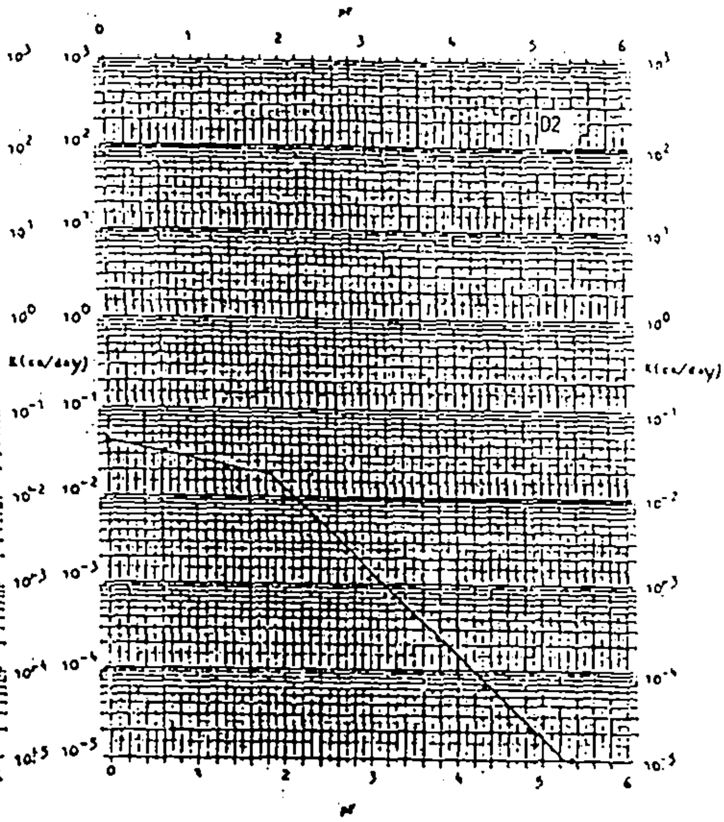






Appendix 7 (Contd.)





APPENDIX 8 COMPREHENSION OF THE MEASURED SOILWATER CHARACTERISTICS (DATAPOINTS) WITH THE DRAWN REGRESSIONLINE FOR THE A-, B2-, C11 AND C12 HORIZONS FOR THE D1- AND D2-HORIZONS ARE THE MEASURED CURVES GIVEN.