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Analog modeling of transient moisture flow in unsaturated soil

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Abstract

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Hydraulic and electronic analog models are developed for the simulation of moisture flow and accumulation in unsaturated soil. The analog models are compared with numerical models and checked with field observations. Application of soil physical knowledge on a soil technological problem by means of steady state considerations, pseudo-steady calculation, numerical models and analog models are compared.

Some examples of application of analog models on drainage requirements are given. From these it appeared that drain spacing is important to avoid water logging, but that drain depth is more important to obtain workable conditions.

Free descriptors: drainage, workability, simulation, amelioration, precipitation, evaporation, soil moisture.

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Contents

1 Introduction

1.1 Purpose

The moisture content of the soil is important for agricultural as well as other land users. It influences water supply to plant roots, aeration, bearing capacity, workability and many other characteristics.

Ameliorationists try to control moisture contents by means of drainage or soil improvement. The purpose of such works can be to avoid very wet soil conditions during rainfall, to obtain more and earlier falling days in which the soil is fit for seedbed preparation, to lower the number of days that sportsfields cannot be used because of a too low bearing capacity, and so on.

The effects of such ameliorations are investigated at a large number of experimental fields all over the world. Many observations have to be made and recorded in such experiments, which make them fairly expensive. A well known disadvantage of this inductive research is the lack of transferability of such experimental results to other soil and weather conditions. This causes a need for repetition at other sites and in other years. Another and better way to increase transferability is to combine field experiments with a deductive explanation of the results. In the past decades, soil physical knowledge has developed far enough to predict the effect of measures. If such a prediction is checked against field observations it can provide a more general validity than even a large number of field trials can give.

The main problem with these predictions is that the effects of such ameliorations on the moisture content of the soil are indirect. The most important factor, the weather, is not influenced by human interference and rainfall and evaporation are causing alterations in soil moisture content far greater than the effects of drainage or soil improvement will impose.

Prediction methods, therefore, must be able to describe the effects of rain and evaporation on moisture content of the soil, especially the topsoil, and it must be possible to do this quantitatively from day to day.

Such predictions can be obtained from simulation models of the unsaturated zone. Numerical models can simulate what happens with the moisture in the soil. With them the flux at different depths and the accumulation of moisture are calculated just as they are happening in reality, provided that the model and the parameters used are correct. Such models generate the moisture content of each layer at any time, including that of the top layer. The time steps used in such models have to be small in order to avoid instability in the calculations. This implies that much computer time is consumed, which makes the simulation of long time-series too expensive for practical purposes.

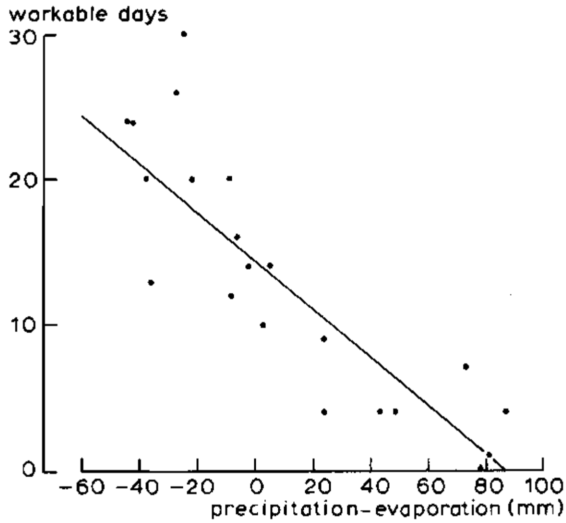


Fig. 1. Relation between precipitation minus evaporation ($0.8E_0$) and number of workable days in March and April in the years between 1951 and 1973 in the Netherlands.

Dealing with long time-series is necessary because of the very irregular distribution of rainfall. Boels & Wind (1975) showed that the unfavourable distribution rather than the high amount of rainfall was responsible for the poor harvesting conditions in the Netherlands in the autumn of 1974. In Fig. 1 the relation is given between precipitation minus evaporation in March and April in the years between 1951 and 1973 and the number of workable days in the same months, as calculated with an analog model. The correlation coefficient is 0.82, which means that the variation in the number of workable days is explained for 67% by the amount of rainfall. The other 33% is to be explained by the rainfall distribution.

Now amounts can be averaged or subjected to a probability analysis, but with distributions this is hardly possible or not at all. In agricultural practice the first date or the first few days with workable conditions in spring is more important than the total number of workable days and the former will be even more dependent on rainfall distribution than the latter. So long time-series must be used to generate data fit for practical application, making numerical models too expensive to use for the prediction of amelioration effects.

This publication deals with the development of simulation models which can be applied to long time-series at very low costs. For this purpose analog models were chosen, because they are continuous in time, having nothing to do with time steps. First a hydraulic analog was developed in which each soil layer is represented by a vessel, its shape being dependent of the moisture characteristic. Unsaturated conductivity is represented by a number of connecting tubes.

Though this model works properly (as will be shown later on), it operates too slow and the adjustment of soil properties is too laborious. In a later stage, therefore, an electronic analog was developed, based upon the analogy between the integrated moisture flux equation and Ohm's law. It operates with great speed and is readily adjustable.

With this instrument most problems about the effect of drainage, soil improvement and other measures on moisture content of soil can be investigated. So, for example, the relation between drain depth and the number of days with insufficient bearing capacity can be studied over a very long period. Drainage requirements of sportsfields in order to avoid days with unplayable conditions of the turf can be determined. The effect of the removal of a compacted layer on water logging and trafficability can be investigated.

Of course the results of the simulations need to be checked against field experiments or field observations, but these can be fairly simple and of short duration because the variability of the results as caused by weather conditions can be calculated with the model.

In this manner long term experiments with many repetitions can be replaced by quick analog simulation in combination with some field checks.

1.2 Basic concepts

For a long time it has been known that moisture conductivity in unsaturated soils depends on moisture content. Before this dependency had been formulated as a mathematical relation, Darcy's law could not be applied to unsaturated soil.

For a basin clay soil Wind (1955a) determined unsaturated conductivity from field observations of moisture content and pressure head. By calculating a regression line between pressure head and unsaturated conductivity the first $k(\psi)$ relation was obtained:

$$k = b(-\psi)^{-n} \tag{1}$$

where k is the conductivity ($cm \cdot day^{-1}$), ψ the soil moisture pressure head (cm); b and n are constants.

It had some disadvantages (difficult integration and incorrect values of k in the vicinity of $\psi = 0$). Therefore later other expressions were proposed, examples are those of Gardner (1958):

$$k = \frac{d}{(-\psi)^n + c} \tag{2}$$

where c, d and n are constants, and of Rijtema (1967):

$$k = k_0 e^{\alpha\psi} \tag{3}$$

where k_0 is the conductivity at zero pressure head and α is a constant (cm^{-1}).

By using such expressions for the $k(\psi)$ relation, the available knowledge of movement of moisture in unsaturated soils could be applied. For that purpose one of the expressions is substituted in Darcy's law, which reads:

$$v = -k \frac{\delta\phi}{\delta z} \tag{4}$$

where v is the volumetric flux in $cm^3 \cdot cm^{-2} \cdot day^{-1}$, ϕ is the total moisture potential expressed as energy per unit weight (cm) and z is the vertical coordinate (cm). In this publication ϕ is denoted as the hydraulic head, being the sum of the soil moisture pressure head ψ (negative in unsaturated condition) and the gravitational head z. The coordinate z has its origin at the soil surface and it is taken positive upwards. Then Eq. (4) can be written as:

$$v = -k(\psi)\left(\frac{\delta\psi}{\delta z}+1\right) \tag{5}$$

Substitution of equations like (1), (2) or (3) in Eq. (5) and subsequent integration results in steady state flux equations (see Section 2.1). Although the use of $n = -1.5$ in the power relation (1) causes a fairly unpractical flux equation, it nevertheless provided a quantitative description of the process of capillary rise.

Such steady state solutions made new practical applications possible, of which Wesseling (1961) and Wind (1955b, 1961) gave some examples. This knowledge resulted in a new problem: that of forecasting.

Observations of the gradients $\delta\psi/\delta z$ from the pressure head profiles allowed to calculate unsaturated conductivity. Once the conductivity relation $k(\psi)$ was known, it should—at least in theory—be possible to do the reverse and calculate moisture profiles from weather data and soil properties. This to be done by combination of the continuity equation (6) with the flux equation (5)

$$\frac{\delta\theta}{\delta t} = -\frac{\delta v}{\delta z} \tag{6}$$

where θ is the volumetric moisture content ($cm^3 \cdot cm^{-3}$, mostly indicated in vol. %) and t is time (days). This gives a non-linear partial differential equation, which has two obstacles to obtain a solution, namely the dependence of the two variables θ and ψ and the dependence of k and ψ. Analytical and semi-analytical solutions can only be obtained for specific cases (for examples see Gardner, 1958; Philip, 1969; Braester et al., 1971; Stroosnijder, 1976; Lomen, 1978; Feddes, 1979/80). These solutions have disadvantages with respect to the restrictive assumptions they generally need. Eq. (6) must be supplemented by appropriate initial and boundary conditions. The initial condition (θ or ψ) can be freely chosen. The bottom boundary condition is to be given in a simple form as a pressure head or a flux (e.g. drain outflow rate). The surface boundary condition also has to be simple, e.g. a specified precipitation or evaporation rate.

Numerical solutions at first were not a practical proposition because of the laborious calculations. With the development of computers their importance increased. Numerical solutions require the same first and second boundary conditions, but the surface condition can be freely chosen for every time step; so variable weather conditions can be incorporated. An example of numerical solutions will be given in Section 2.4.

Before dynamic models could be applied, other ways were explored to apply the knowledge of moisture in the unsaturated zone. A makeshift solution was found in the shape of pseudo-steady state sequences. They were used to calculate the amount of moisture which can be extracted by plants below the root zone (Wind & Hidding, 1961). Pseudo-steady state models presume a sequence of steady state situations, with in each situation a new, mostly higher, flux or groundwater depth. They are discussed in Section 2.3.

Dynamic numerical models are now available, but they are only used for short time series. Because of the many calculations needed, they consume so much computer time that they are too expensive to use for long time-series. Nevertheless long time-series are necessary to solve problems like drainage requirements or the effect of groundwater depth on evapotranspiration.

Therefore models other than dynamic numerical ones are used to solve practical problems. The use of the makeshift solution by means of pseudo-steady state models is continued (de Laat, 1976) but also analog dynamic models were developed. The first of these is a hydraulic analog (Wind, 1972) which is discussed in Section 3.1. A recently developed electronic analog by Wind & Mazee (1979) will be treated in Section 3.2.

The greatest advantage of analog models is their negligible operation cost, which makes them appropriate to deal with long time-series. The most striking disadvantage is caused by limitations in the analogy which make them less versatile than numerical models.

A comparison of different calculation methods and models applied to a practical problem is given in Chapter 4. Finally, Chapter 5 deals with the application of the models developed.

1.3 Assumptions

In order to apply soil physical knowledge to practical problems by means of models some schematizations had to be made.

The soils are thought to have physical properties, as $\psi(\theta)$ and $k(\psi)$ relations, which do not change with time. So swelling and shrinking are neglected and compaction is thought not to occur. For soils with cracks the discussed models are not feasible (Bouma, 1977).

The effects of hysteresis are not taken into account. Changes in soil properties as well as hysteresis are of practical importance; neglecting them therefore restricts the applicatility of the models. To include these effects, however, would make the model too complex for practical application at this moment.

Darcy's law is assumed to be valid and only vertical flow is considered. In both the numerical model of Wind & van Doorne (1975) and the electronic analog of Wind & Mazee (1979), the $k(\psi)$ relation is thought to be exponential. According to Rijtema (1965) this confines the applicability of the models to fairly wet conditions. The hydraulic analog of Wind (1972) can be used with $k(\psi)$ relations of any shape.

Flux due to differences in salt concentrations of soil moisture and to temperature gradients is neglected. The flow of moisture to an ice front also is not taken into account. No difference is made between rain and snow in the input of the models. This makes the model output unreliable during frost periods and the differences in the moisture distribution generated in the model and those occurring in reality during frost periods can make the results unreliable for a considerable time after such periods.

In the mentioned numerical and electronic models potential evaporation is used as an input. The effect of a dry top soil, reducing the evaporation in reality, is not taken into account. In the hydraulic model evaporation is made dependent on the moisture suction in the top soil. A device reducing evaporation is being built into the electronic analog. All mentioned models are simulating evaporation at the soil surface; uptake of water by roots is not taken into account. This restricts their validity to bare soil or soils with shallowly rooting crops.

Assumed is a linear relation between drain outflow and hydraulic head, which in reality often is not the case.

1.4 Notation and sign conventions used

A drainage intensity (day^{-1}), the ratio between drain outflow rate and hydraulic head midway between two drains
a dimensionless factor $a = e^{\alpha \Delta z}$
D drain depth in cm below soil surface
E electric potential (V)
h height above groundwater (cm)
i electric current (A)
k hydraulic conductivity in unsaturated state ($cm \cdot day^{-1}$)
k_0 conductivity at zero moisture pressure ($cm \cdot day^{-1}$)
R electric resistance (Ω)
t time (day)
v vertical flux ($cm \cdot day^{-1}$) upward is positive
z vertical distance from soil surface (cm) positive upwards
z also gravitational head (cm)
α exponent used in Rijtema's $k(\psi)$ relation Eq. (3) (cm^{-1})
ψ soil moisture pressure head (cm) in unsaturated zone negative
ϕ hydraulic head (cm), sum of ψ and z
θ volumetric moisture content ($cm^3 \cdot cm^{-3}$ or vol. %)

Some other, incidental, symbols are defined in the text only.

2 Some other methods

2.1 General

Before dynamic models of the unsaturated zone were available, calculation of moisture contents in dependence of time was not possible or only possible under simple conditions. Nevertheless investigators did try to predict the effect of some measures on soil moisture content. This was done for example to study the effect of drainage on workability and the effect of soil improvement on available moisture.

Methods to obtain a certain prediction are dealt with in this chapter. They are steady state considerations, pseudo-steady state sequences and a numerical model. Although the latter already is a dynamic model it is discussed here because of its practical unsuitability with regard to long time-series.

Another method, using analytical solutions, is not treated here; reference is made to Stroosnijder (1976). This is done because analytical solutions can only be obtained under rather restrictive assumptions.

2.2 Steady state flux equation

When the $k(\psi)$ relations of Section 1.2 are combined with Darcy's law, flux equations can be developed.

If Rijtema's $k(\psi)$ relation (3) is used Eq. (5) can easily be integrated. This results in:

$$\psi = -h + \frac{1}{\alpha} \ln\left(1 - \frac{v}{k_0}(e^{\alpha h} - 1)\right) \tag{7}$$

where h is the height above groundwater level.

Integration of Eq. (5) with the use of Wind's (1955) or Gardner's (1958) $k(\psi)$ relation results in less simple equations. Their general shape depends on the value of the exponent n, as Wind (1961) has shown.

As the laboratory or field determinations of k show considerable variability, the choice between adjustions according to Wind, Gardner or Rijtema is arbitrary. Nevertheless the influence of this choice can be important. Fig. 2 gives two $k(\psi)$ relations, a Gardner power curve (8) and a Rijtema exponential curve (9), which cross each other:

$$k = \frac{150}{(-\psi)^{1.5} + 50} \tag{8}$$

$$k = 3e^{0.03\psi} \tag{9}$$

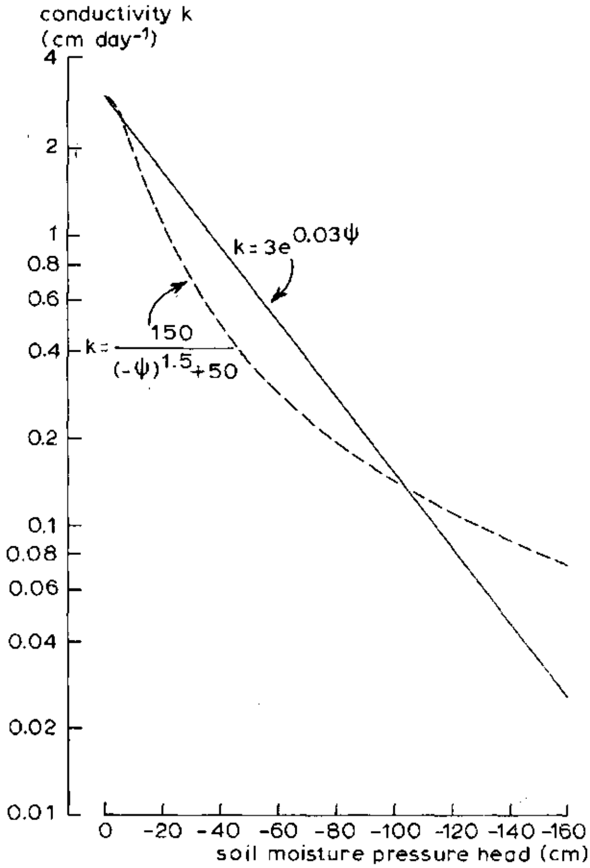


Fig. 2. Exponential and power relation between conductivity and pressure head.

The effect of the difference between those relations on steady state pressure head profiles is shown in Fig. 3. When the flow direction is downward, the power curve, due to its lower conductivity in wet soil, indicates wetter conditions than the exponential curve. For upward flow the reverse holds up to a certain limit, and then the larger conductivity of the power curve plays an important role. Up to a height of 80 cm above groundwater level the differences in ψ between the calculated curves are less than 20 cm. For the wettest curves the difference is 12 cm at a mean value of -40 cm soil moisture pressure head at the surface. So the arbitrary choice can have a major influence in steady state pressure head profiles.

It is to be expected that its influence in the non-steady state is similar but smaller. Then moisture contents are primarily governed by precipitation and evaporation. The secondary influence of soil properties is governed both by the $k(\psi)$ and $\psi(\theta)$ relation. To demonstrate what is remaining of the influence of the choice between a power curve and an exponential curve, a non-steady state calculation has been made. To that end finite difference models were used, based on equations (5) and (8), and (5) and (9) respectively. In both models the slope in the $\psi(\theta)$ relation was constant at 0.1, which means that the moisture loss at

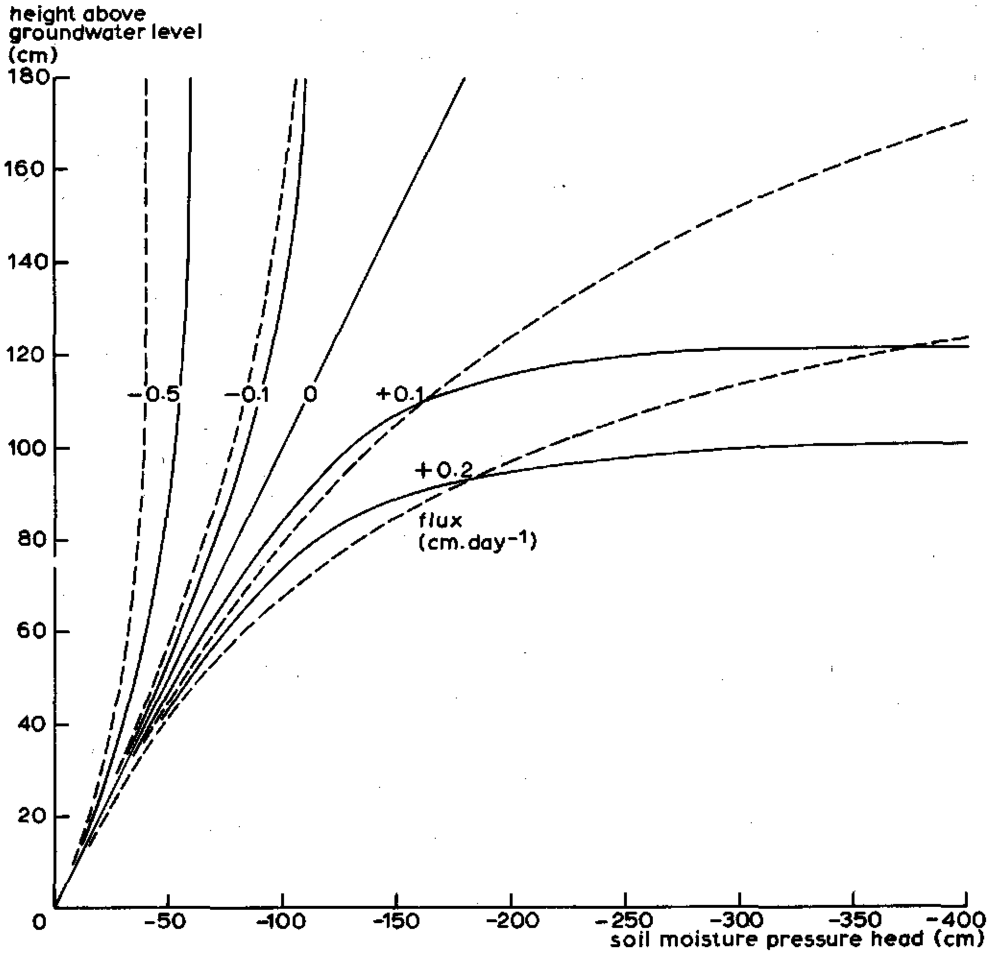


Fig. 3. Steady state soil moisture pressure head profiles calculated with the exponential curve (——) respectively power curve (---) of Fig. 2.

$\psi = -100$ cm is 10%. The initial condition taken was a static equilibrium with a groundwater depth of 80 cm; the latter was kept constant at every time. The evaporation-precipitation sequence was: 1 day with 0.5 cm rain followed by 7 days with 0.2 cm $\cdot$ day^{-1} evaporation and then 5 days with an evaporation rate of 0.5 cm $\cdot$ day^{-1}. Fig. 4 gives the result. The differences between the pressure head profiles calculated with the power respectively exponential curve are clearly smaller than in Fig. 3. It can be concluded that steady state considerations require a higher accuracy in the knowledge of soil properties than dynamic models.

With steady state flow equations, the flux between two pressure head values at a certain distance can be calculated. For example between zero pressure head at groundwater level and a soil moisture pressure head of −16,000 cm in the root zone. So if it is known how much moisture per day is required to rise from below the root zone, the appropriate groundwater depth can be calculated.

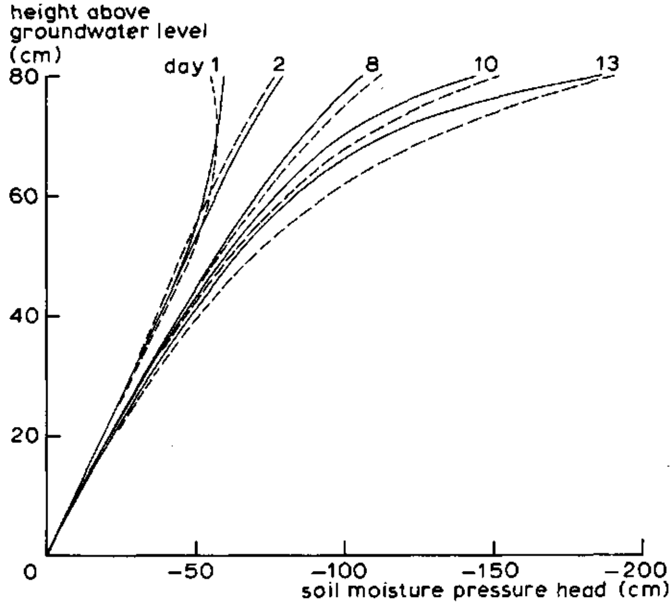


Fig. 4. Non-steady state soil moisture pressure head profiles during a time sequence calculated with finite difference models based on exponential (——) and power (- - -) $k(\psi)$ relations. From static equilibrium at zero time 0.5 cm precipitation until day 1; 0.2 cm · day^{-1} evaporation until day 8 and 0.5 cm · day^{-1} evaporation until day 13.

There are some problems, however. The amount of moisture required changes from year to year and from day to day; the moisture uptake from below the root zone is only partly extracted from below the groundwater table and the latter is seldom at a constant depth. The question which is the best depth of groundwater table is clearly a non-steady state problem and steady state flow equations can only give a rough indication.

So there is need for a method not only dealing with flow of moisture but also with moisture accumulation and depletion, i.e. a non-steady state method.

2.3 Pseudo-steady state sequences

Because steady state considerations are not giving a quantitative solution of soil moisture problems, other methods had to be developed. The need for this was already felt before computers could perform the elaborate calculations required for dynamic simulation models. Wind & Hidding (1961) developed a method to calculate the amount of accessible moisture below the root zone over a certain period. With approximately the same method Wind (1963) calculated the time used to reach a certain moisture content in the top soil at a given evaporation rate.

The principle of this method is the assumption that moisture extraction takes place according to a succession of steady state moisture profiles. Every steady state profile is fully determined by two data; these can be the values of ψ at two depths z, or one such point and the flux. To calculate the amount of accessible moisture below the root zone, the boundary condition $\psi = -16{,}000$ cm at the lower end of the root zone has been chosen. This was combined with a number of decreasing fluxes, each of which yielded a pressure head profile, see Fig. 5. The amount of moisture between two profiles can easily be calculated. If one assumes that the extraction rate is the mean of the fluxes of the two profiles it can be calculated how long the extraction lasts. After calculating this transition time for every pair of fluxes, the total amount of moisture below the root zone accessible within a growing season can be found. Because of the choice of the boundary condition $\psi = -16{,}000$ cm this is the maximum available amount. In reality the amount will be smaller because it takes some time before that boundary condition is reached.

This method was used to calculate either the amount of accessible moisture in a given period or the time required for the drying out of the profile to a certain degree. It can also be used in a simulation model. This has been developed by Rijtema (1970) and de Laat (1976) who called it the pseudo-steady state model.

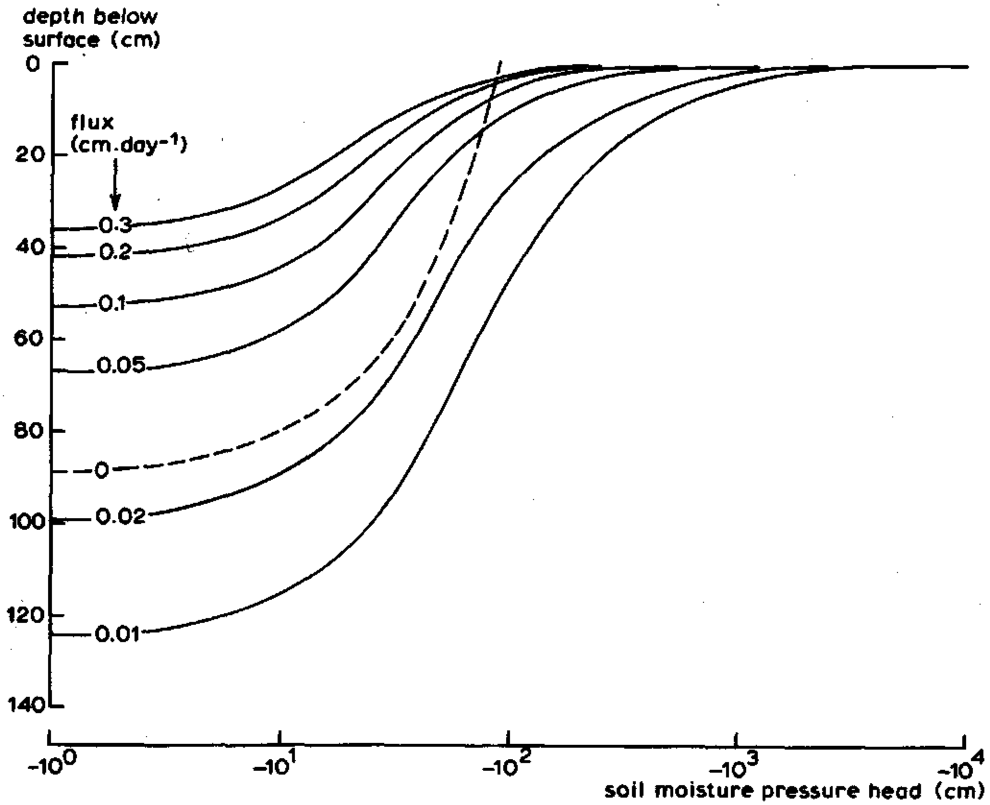


Fig. 5. Soil moisture pressure head profiles in a sandy soil (——) with boundary condition of $\psi = -16{,}000$ cm at zero depth and the corresponding fluxes and one profile (- - -) with boundary condition groundwater table at 90 cm depth and zero flow. After Wind & Hidding (1961).

In steady state flow the flux is constant both in time and depth; in dynamic models flux is varying in time as well as depth. In pseudo-steady state models flux is assumed to be constant in depth but varying in time. Though this assumption is unrealistic, it had to be made to perform quantitative calculations, formerly because dynamic models were not available, now because they are too expensive.

It is not easy to estimate the deviations caused by this erroneous assumption. However, the results of pseudo-steady state calculations can be compared with those of dynamic models; an example of this is the following.

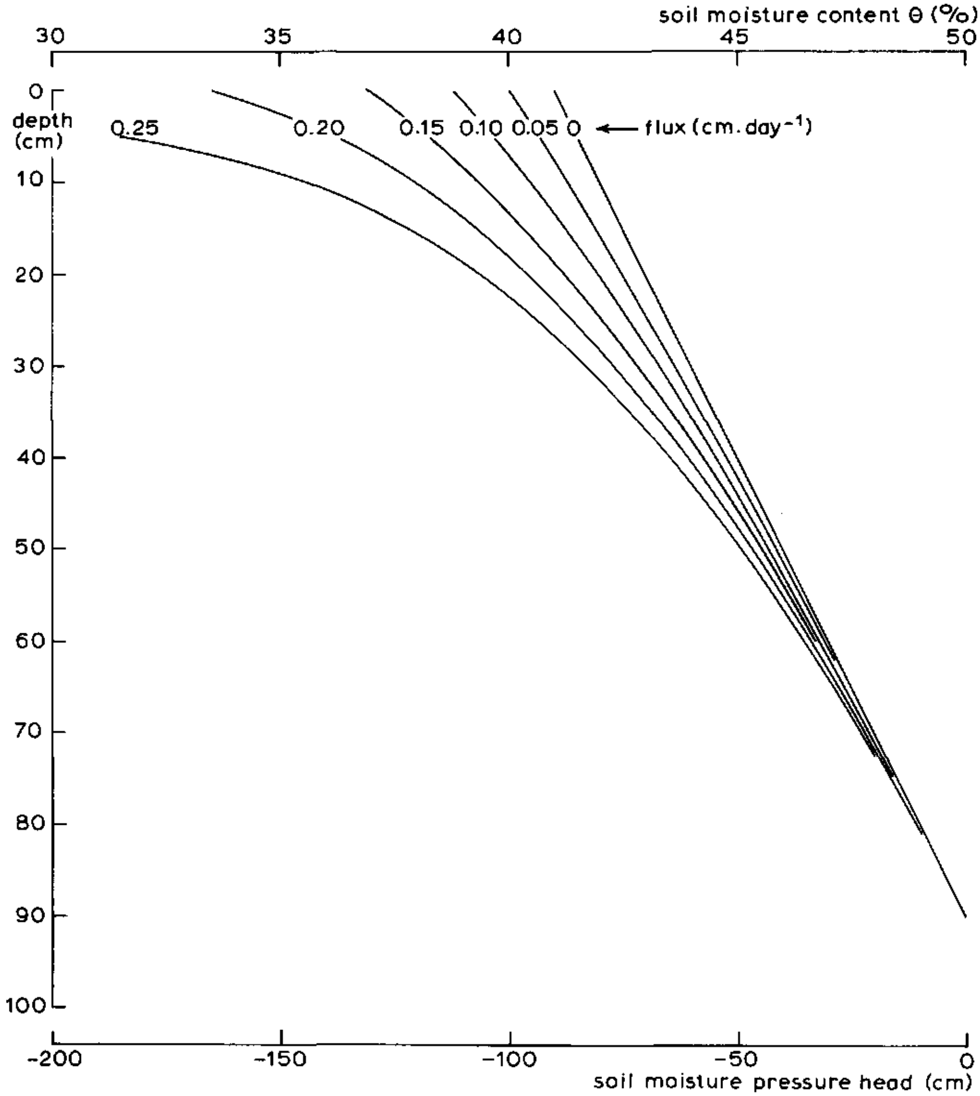


Fig. 6. Steady state moisture profiles for six upward fluxes and a constant groundwater depth at 90 cm.

A soil with a controlled groundwater table at 90 cm depth is evaporating at its surface with a continuous rate of 0.25 cm · day^{-1}. The initial condition at time $t = 0$ is zero flow. The soil physical properties are:

$$\psi = 10\theta - 500 \qquad (\theta \text{ in vol. \%})$$
$$k = 2e^{0.025\psi}$$

The steady state moisture profiles are given in Fig. 6 for $v = 0$; 0.05; 0.1; 0.15; 0.20 and 0.25 cm · day^{-1}. From this figure the total amounts of moisture in the unsaturated zone pertaining to the mentioned fluxes can be read. These are shown in Table 1, column 2. The differences between them are the amounts of moisture which are to be extracted before a new steady state is reached, column 3. The extraction rate, column 4, is the difference between evaporation rate (0.25 cm · day^{-1}) and mean flux. By dividing column 3 by column 4 the duration of the extraction is found (column 5). The moisture contents at 5 cm depth belonging to the mentioned steady state steps, can be read from Fig. 6 and are given in column 7.

The moisture contents at 5 cm depth also have been calculated with the FLOW-model of Wind & van Doorne (1975) under the same conditions, see column 6. Comparison of columns 5 and 6 shows considerable differences: the pseudo-steady state method overestimates the time to reach a certain moisture content. This is caused by an overestimation of capillary rise which is inherent to this method. In Fig. 7 the vertical fluxes at 90 cm depth are shown as calculated with the FLOW-model and as assumed by the pseudo-steady state method. At first, the pseudo-steady state method overestimated capillairy rise; after 8 days the differences became negligible.

In this example with a constant groundwater table, the drying time is overestimated by the pseudo-steady state method. In another example, see Chapter 4,

Table 1. Moisture extraction by a 0.25 cm · day^{-1} evaporation rate from the surface of a soil (see text) with a constant groundwater table depth of 90 cm. Data calculated by the pseudo-steady state method and by the dynamic model FLOW.

Flux (cm day^{-1}) 1	Total amount of moisture (cm) 2	Difference (cm) 3	Extraction rate (cm · day^{-1}) 4	Duration extraction: pseudo-steady state method (days) 5	Duration extraction: dynamic model (days) 6	Moisture content at 5 cm depth (%) 7
0	40.950					41.50
		0.265	0.225	1.18	0.50	
0.05	40.685					40.65
		0.306	0.175	2.93	1.66	
0.10	40.379					39.60
		0.368	0.125	5.87	3.80	
0.15	40.011					38.30
		0.451	0.075	11.88	9.23	
0.20	39.560					36.15
		0.840	0.025	45.48	∞	
0.25	38.720					31.30

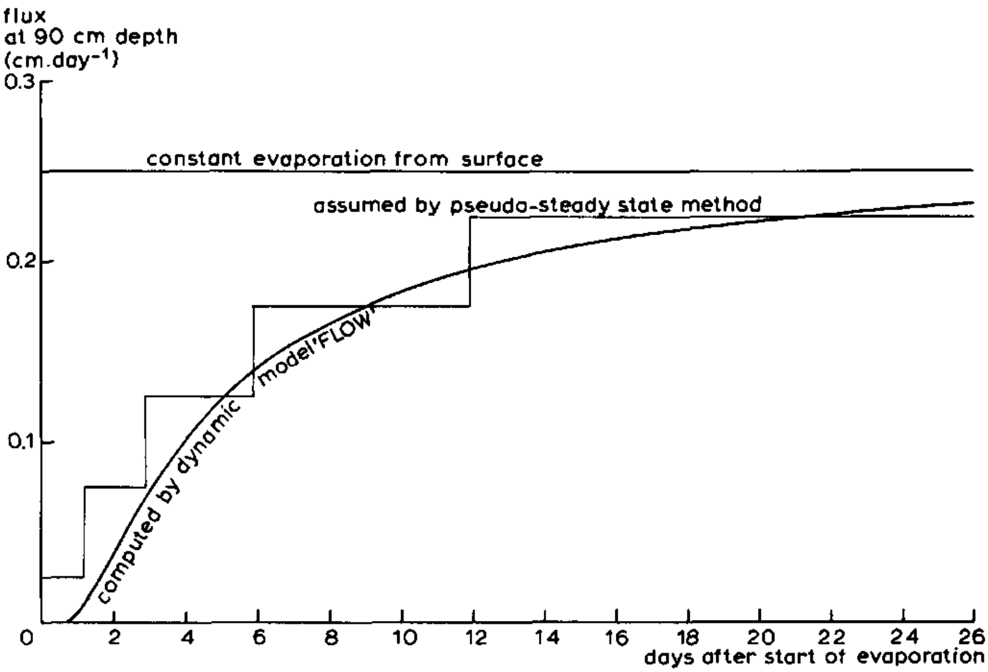


Fig. 7. Capillary rise rates (fluxes at 90 cm depth) as a function of time, computed by dynamic model FLOW and by the pseudo-steady state method.

with a falling water table, drying time is underestimated by this method. So some doubt is indicated about the accuracy of the pseudo-steady state method.

2.4 Numerical model FLOW

For many purposes the effect of actual rainfall on the moisture condition of the topsoil must be calculated. Workability improvement by drainage is such a purpose. It can of course be studied, without calculations, on experimental fields, but because of the tremendous variability in amount and distribution of rainfall such experiments have to last many years. Therefore reliable information from such experiments often comes at too late a time. By calculation one can make use of recorded rainfall data of the past, assuming that the climate is not changing. Thus the results are available in a short time.

To this end Wind & van Doorne (1975) developed a numerical model of the unsaturated zone. The input of the model consists of:

- natural precipitation and evaporation
- maximum value of pool depth (surface storage)
- moisture characteristic in table form
- $k(\psi)$ relation in the form of the expression of Rijtema (1965)
- drain depth
- drain intensity

The output provides information about:
- actual pool depth
- run-off
- depth of groundwater table
- drain discharge
- moisture content and pressure head at every depth

2.4.1 *Averaging conductivity values*

In order to calculate the flux, the discrete shape of flow equation (5) is needed:

$$v = -\bar{k}\left(\frac{\Delta\psi}{\Delta z}+1\right) \tag{5a}$$

A certain depth interval $\Delta z = z_2 - z_1$ is to be selected; the gradient of ψ over this interval is $\psi_2 - \psi_1$. Moreover a certain average value of k has to be chosen somewhere between the k-values pertaining to ψ_2 and ψ_1. The procedure changes the differential equation into a finite difference equation. Van Keulen & van Beek (1971) took for $\bar{k}$ the arithmetic mean, Feddes et al. (1978) are using both the geometric and arithmetic mean.

The model of Wind & van Doorne (1975) makes use of the integrated flux equation:

$$v = \frac{k_2 - ak_1}{a-1} \qquad (a = e^{\alpha\Delta z}) \tag{10}$$

This expression is obtained under the assumptions that ψ is a differentiable function of z, that v is constant over the depth interval during the time interval and that an exponential $k(\psi)$ relation exists. This integrated expression was chosen because of its simplicity, which reduces computer cost.

It appeared that Eq. (10) yields better results than the difference equations with an averaged k. For steady state conditions Eq. (10) is certainly correct; fluxes calculated according Eq. (5a) with a harmonic or geometric mean often differ more than one order of magnitude from the true flux. The arithmetic mean gives the least deviation, but in some cases even the thus calculated velocity is 3 to 7 times higher than it should be.

The errors are counter-balanced by the feed-back system automatically present in such calculations. A flux calculated too high causes gradients to decrease and therefore also decreases flux. However, the errors made are so large that they perceptibly influence the calculated moisture profiles.

The effect of errors caused by averaging conductivity values depends on the depth interval. If this is very small, the effect is negligible. The choice of depth intervals has, however, large consequences with regard to computation costs.

2.4.2 *Choice of time and depth intervals*

Because computing costs decrease with an increase of step size it was tried to maximize the latter. The choice of depth interval depends on the accuracy to be achieved; the time interval can freely be chosen up to a certain limit. Too large time steps cause oscillations in the results with amplitudes increasing at each step.

The assumption that flux is constant during the time interval introduces errors. The cause of oscillation is that these errors are amplified during the next time step. Amplification is proportional to time step size, so the time interval is to be chosen such that the absolute value of the amplifier is smaller than 1. In that case any error made is reduced in the next time steps. The condition for stability is:

$$\Delta t < \Delta z \cdot \frac{e^{\alpha \Delta z} - 1}{e^{\alpha \Delta z} + 1} \cdot \frac{d\theta}{dk} \tag{11}$$

This means that the time interval should be:
- inversely proportional to k_0
- about proportional to α
- about proportional to the square of Δz

2.4.3 Computing costs

The costs of simulation of one day strongly depends on the choice of layer depth and also on the conductivity of the soil. Thin layers and coarse soils give high computing costs. With the discussed numerical model the simulation costs of one day vary between Dfl 1 and 10 (US $ 0.4 to 4.0).

For runs simulating several years computing costs are prohibitive, which means that cheaper ways of calculation must be found.

3 Analog models

3.1 Hydraulic model

The flux in the unsaturated zone in the soil is the product of conductivity and gradient. The main problem in modeling the unsaturated zone is that conductivity does not have a constant value but depends on the moisture content of the soil, the calculation of which is the aim of modeling.

A method to break through this interrelation is to construct a contraption in which conductivity automatically depends on moisture content. Such a solution has been found in a hydraulic model in which the moisture content in the soil is represented by the amount of water in a vessel and in which the conductivity is represented by a number of tubes connecting two vessels at many levels. Nearly full vessels (wet soil) are connected to their neighbour by many tubes (high conductivity). Nearly empty vessels (dry soil) are connected with as many tubes, but only a few of them can conduct water because the other ones are above the water table in the vessels. Fig. 8 gives an outline of the hydraulic model used by Wind (1976) for the simulation of workability.

This is a very simple solution for a problem the author already tried to solve twenty years ago. It is not a question of technical evolution during that time; the analog could have been constructed in 1955 when knowledge about the $k(\psi)$ relation became available, but this particular idea did not come to mind. It later originated when reading a hobby journal containing an article on automation of model railways. An electronic circuit was explained to the readers with the aid of the analogy with a hydraulic example: a vessel that was emptied by openings at three levels. Suddenly the idea came to realize the automatic dependency of moisture content and conductivity with a hydraulic model.

3.1.1 Development of the model

Whereas the concept of the model was very simple, some problems had to be solved during the development. The first was that vertical flow deals with two heads; conductivity is controlled by soil moisture pressure head, but flux is controlled by the gradient in hydraulic head. This could be solved by placing the vessels at different heights, so that the height of the water table in a vessel represents the hydraulic head ϕ and the distance between water table and the top of the vessel represents ψ. The possibility to express the two potentials involved in the flow process by one medium is an enormous advantage of the hydraulic analog above an electric one.

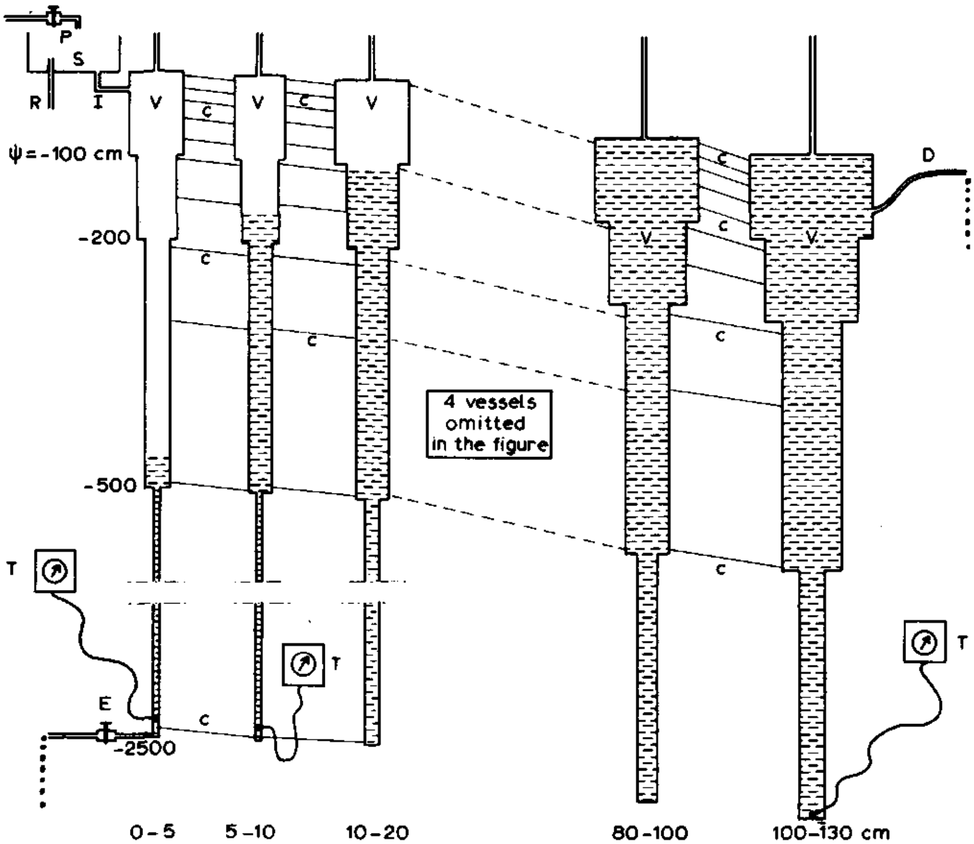


Fig. 8. Outline of a hydraulic analog. V vessels representing soil layers of a certain thickness and moisture characteristic; C connecting tubes, representing hydraulic conductivity; P precipitation valve; E evaporation valve, both valves commanded by a papertape reader; S surface tank; R run-off pipe; I infiltration tube; D drainage tube; T pressure transducer, connected with data logger.

The shape of the vessels had to be chosen such that if the amount of water in them is representing moisture content, the water level represents soil moisture pressure head. A cylindrical vessel represents a straight moisture characteristic, a conical vessel a curved one. Generally the shape of the vessels must be proportional to the first derivative of the moisture characteristic to ψ.

The connecting tubes give a discrete imitation of the continuous relation between conductivity k and soil moisture pressure head ψ. The possibility to choose both length and diameter, as also the number of connecting tubes, allows a good approach. The drainage of the soil can be represented by a tube connected to the vessel at a level representing drain depth. Its length and diameter determine drain intensity. Rainfall is represented by adding water to the first vessel, evapotranspiration by extracting water from it.

3.1.2 Selection scales

Three scales are involved in this model:
S_v, the vertical scale, is the length (m) in the model representing one meter in depth or pressure head in reality;
S_a, the scale for area is the amount of water (cm^3) in the model representing one cm of water in reality. This scale has the dimension l^2, it gives the surface area of a soil column in which the amount of water is the same as in the model;
S_t, the time scale, is the model time representing one real day.

The selection is the result of a number of compromises. A small time scale gives the opportunity to make many observations in short time, but it also causes a turbulent flow in the tubes. A large vertical scale promotes accuracy but it increases model size. The same holds true for the area scale; moreover a large S_a may cause turbulence to appear.

Although there is large degree of freedom in the choice of scales, the time scale cannot be chosen very small because it confines the maximum conductivity which can be represented by the model. Mostly used was a model time of 5 minutes representing one real day. This makes the hydraulic analog a rather slow model. Simulation of 4 months each over 23 years took about 10 days of continuous operation. Once automation of the model was achieved, simulation of long runs was possible with negligible costs.

3.1.3 Two errors in the model

The flow of water through the tubes has the correct value when both ends of the tubes are below the water tables of the vessels they connect. If there is a considerable difference in moisture content between two layers, there is also a large difference in water level in two adjacent vessels. A number of connecting tubes then ends above the water table in the 'driest' vessel. In that case two serious errors are made:

- the gradients in the tubes ending above a water table are lower than they should be;
- the conductivity is determined by the wettest vessel while it should be an average as determined by both vessels.

The effect of each of these errors on the flux can be large but they are working in opposite directions: the gradients are too low, the conductivity is too high. The combined effect of the two can be calculated. The flux in the model is:

$$V_m = \frac{k_2 - k_1}{\alpha \Delta z} - k_1 \qquad (12)$$

and it should be:

$$V = \frac{k_2 - k_1}{e^{\alpha \Delta z} - 1} - k_1 \qquad (10)$$

With increasing $\alpha\Delta z$ the deviation between the two equations increases at first, but when $\alpha\Delta z$ becomes still larger the influence of the fraction term is becoming less. So there is a maximum deviation of 30% occurring when $\alpha\Delta z = 1.8$ and $k_2 = 0$. The deviation can be confined by the choice of Δz.

The above concerns deviations in steady state situations. In reality they will be much smaller, as they are reduced by a feedback system present both in soil and model. It appeared that a good similarity was found between the moisture distributions calculated by the hydraulic analog and a numerical model in a non steady situation.

In Chapter 5 some applications will be shown in which drain depth and drain intensity are varied, the former seeming more important than the latter. The most striking example, however, is that of a simulation over 6 months of pressure head in the top soil, drain discharge and depth of groundwater table.

There are, however, other problems: the model is fairly slow by simulating one day in 5 minutes and any change of soil properties is laborious. Therefore another model was developed, an electronic analog.

3.2 Electronic analog ELAN

It was tried to find a concept for a model combining the advantages of the hydraulic analog (low costs) as well as of the mathematical model (velocity and easy adjustability). This was realized in an electronic analog, developed in cooperation with the Technical and Physical Engineering Research Service (TFDL, Wageningen), see Wind & Mazee (1979).

At first it was tried to make an electrical model based on the same principles as the hydraulic analog. Moisture pressure head should be represented by electric potential and conductivity by resistors. The connecting resistors could be opened and closed by electronic valves, commanded by the electric potential. It appeared to be very difficult, however, to avoid the occurrence of the same errors as present in the hydraulic analog. There a wrong conductivity and a wrong gradient are compensating each other. In an electrical copy a wrong conductivity would also occur but the gradients will be correct. So a device had to be made to introduce the correct conductivity. This was found, but it made the model too expensive.

Some years later a new idea was born: an electronic analog based on the same integrated flow equation as Wind & van Doorne's (1975) numerical model. In this model the electric potential does not represent pressure head but conductivity. Electric resistors are representing the factor $a = e^{\alpha\Delta z}$. A steady state model of this type could be made in some minutes from a couple of resistors.

The principle of the model is the resemblance between Wind & van Doorne's flow equation:

$$v = \frac{k_2/a - k_1}{\frac{a-1}{a}} \qquad (10)$$

and Ohm's law:

$$i = \frac{E_2 - E_1}{R} \tag{13}$$

If conductivity k_1 is represented by electric potential E_1, flux v by electric current i and the value $(a-1)/a$ by resistance R, the potential E_2 represents the conductivity k_2 divided by a.

3.2.1 *Development and scales of the model*

The division of k by the factor a accumulates with depth, so that in layer number n the electric potential E_n represents k_n divided by a^{n-1}. To avoid this accumulation, in every junction (layer) an amplifier is installed multiplying the potential with the adjustable factor a.

Every layer contains a capacitor, the charge of which represents moisture content θ. As the relation between moisture content and conductivity is not a linear one a function generator is also required. In this procedure the $k(\theta)$ relation is divided into three straight line segments.

In this model the choice of time scale is nearly unconfined; it has been chosen at 2 seconds representing one day to make it possible to use line recorders and tape-writers. A velocity of $1 \text{ cm} \cdot \text{day}^{-1}$ is represented by $10\ \mu\text{A}$ and a conductivity of $1 \text{ cm} \cdot \text{day}^{-1}$ by $\frac{1}{3}$ V.

The model contains 10 layers and in each of them the values of conductivity and moisture content can be read without affecting the functioning of the model. Fig. 9 gives a picture of the model.

Rain and evapotranspiration are fed into the model's top layer with a paper tape reader. A device is in preparation which can reduce evaporation in dependency of the moisture condition in the first layer. In off position of the tape reader, an adjustable constant rain rate is applied.

3.2.2 *Special functions*

A device representing the soil surface is called 'top layer'. If the precipitation rate exceeds the infiltration rate, the difference is ponded upon the surface; in the model electricity is stored in a capacitor. A function generator, adjustable for k_0 and α, translates the amount of ponded water into the corresponding value of k.

The lowest soil layer is connected with a device, called 'drain layer'. The drain is thought to be in the middle of the lowest layer. Because the drain discharge rate of a given system in a given soil is governed by the positive pressure head ψ and not by the varying value of k, a logarithmic module is used. The soil values α and k_0 and the drain intensity A can be adjusted. So drain depth and drain spacing can be chosen freely.

The principle on which the model is based, the resemblance between Ohm's law and the integrated flow equation, gives problems with non-homogeneous soils. Between two soil layers of different composition the values of θ and k, both

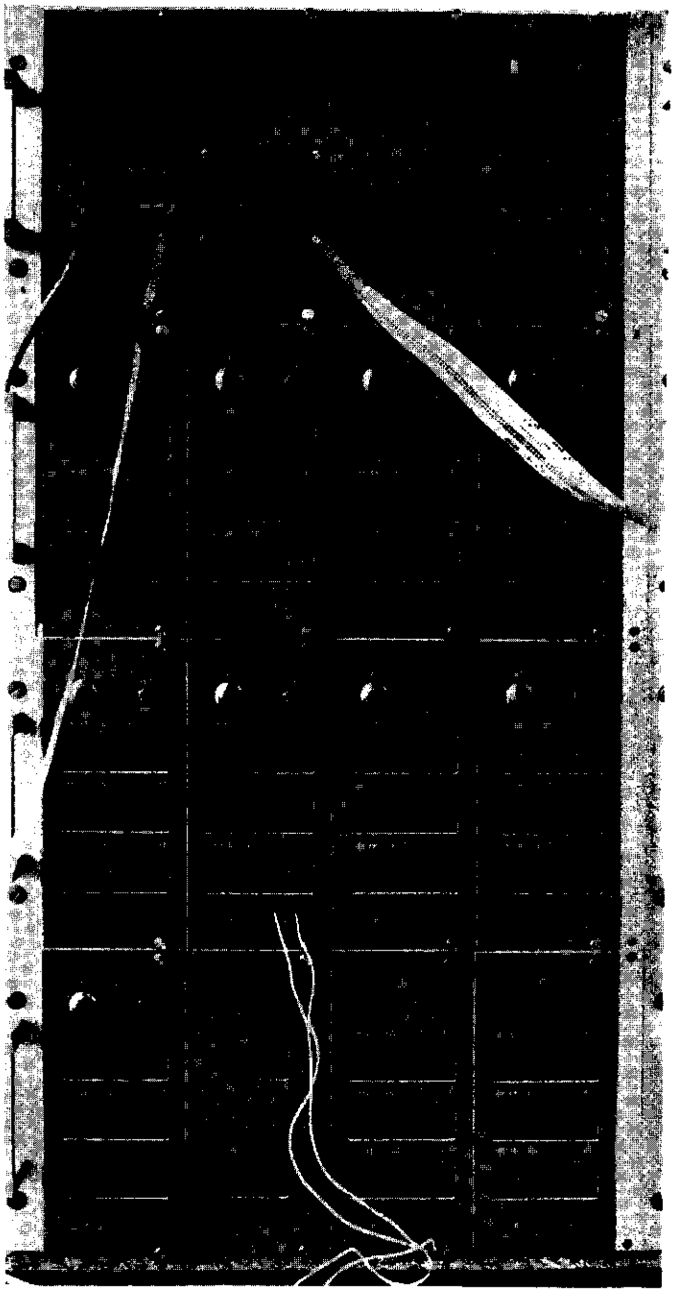


Fig. 9. Electronic analog ELAN. With thumbwheel switches the $k(\theta)$ relation can be adjusted, the potentiometer gives the value of $a = e^{\alpha \Delta z}$.

present in the model, are different at the boundary; the value of ψ is the same, but this factor does not operate in the model.

In the model transition layers are used which translate the value of θ in the upper layer into the value of k that it should have if it had the same composition as the lower layer. The transition layers at the boundary between two differing soil layers consist only of a function generator, whereas resistor and capacitor are absent. The $k(\theta)$ relation in such a transition layer is to be composed of the $\psi(\theta)$ of the upper soil and the $k(\psi)$ of the lower soil.

In principle the electric analog should have an additional circuit for representing saturated flow. Up to now this is not the case. So in saturated conditions the model is operating with the same equations as in unsaturated conditions. The value of θ can not increase above its maximum, i.e. saturation, value. The conductivity, which should be k_0 in this condition, can exceed this value manyfold, however. This results in too deeply calculated groundwater levels. This must be counter-balanced by using a calculated equivalent value of drainage intensity.

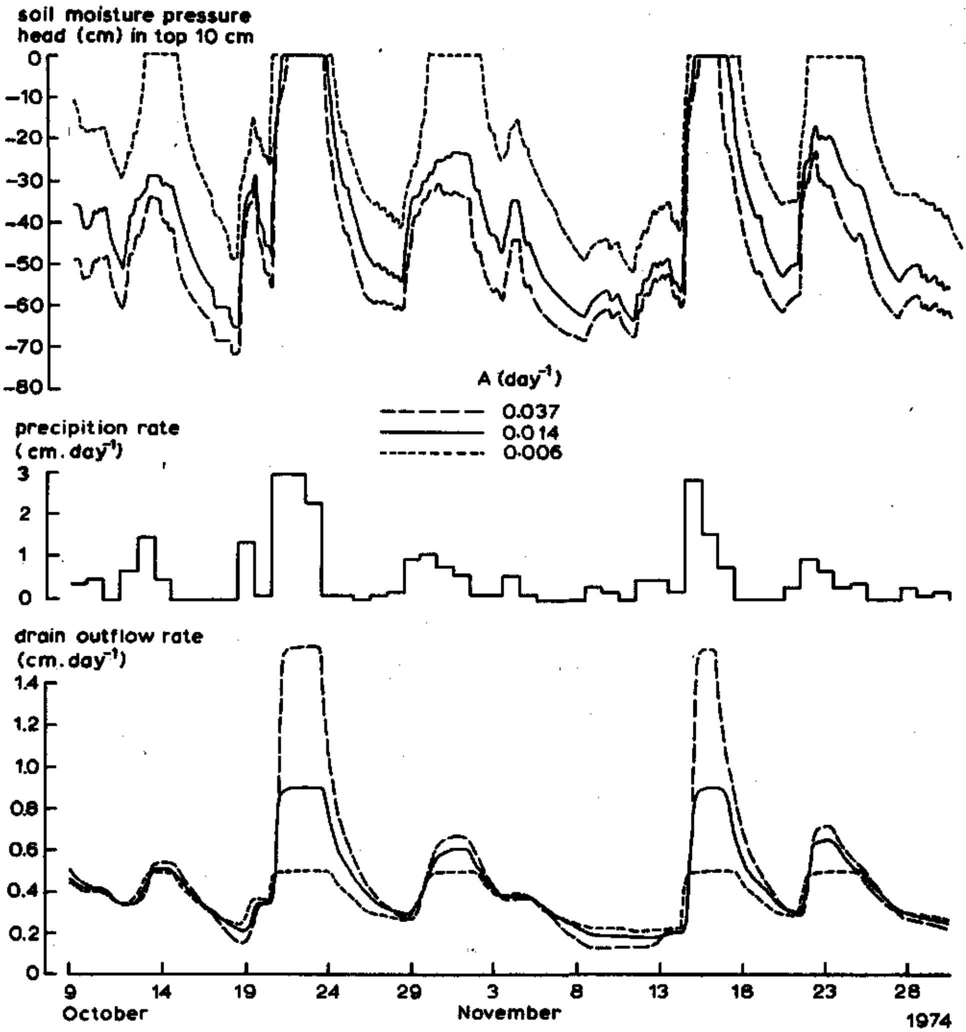


Fig. 10. Effect of drain intensity A on moisture pressure head in the topsoil in the wet autumn of 1974, computed with the electronic analog ELAN.

3.2.3 *Examples of use*

In the paper of Wind & Mazee (1979) examples are given to compare the electronic analog with numerical models; this comparison will be dealt with in Section 5.2.

Three other examples are given here to show some problems to which the model can be applied. The first of these, see Fig. 10, is the simulation of the soil

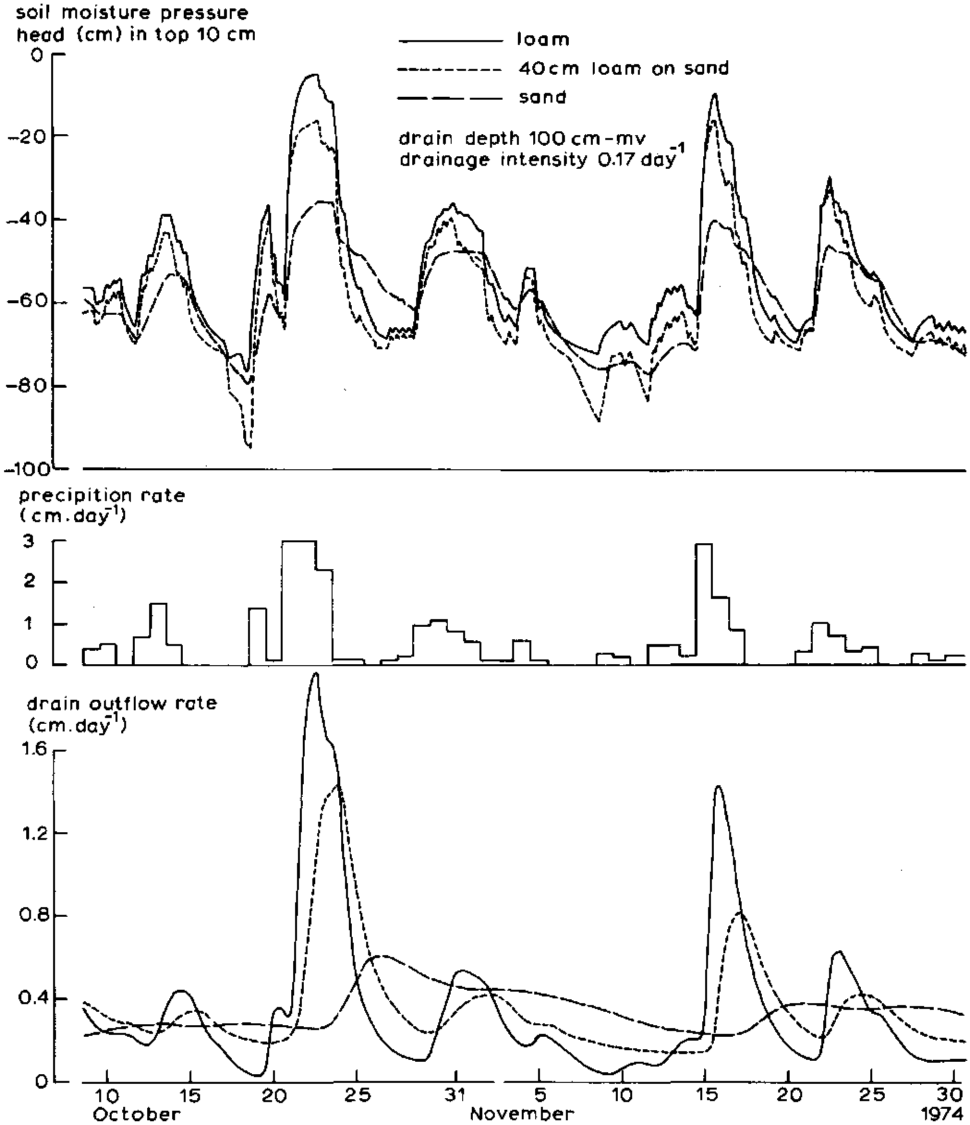


Fig. 11. Precipitation, soil moisture pressure head in the top 10 cm and drain outflow in three soils during the autumn of 1974 as simulated with ELAN.

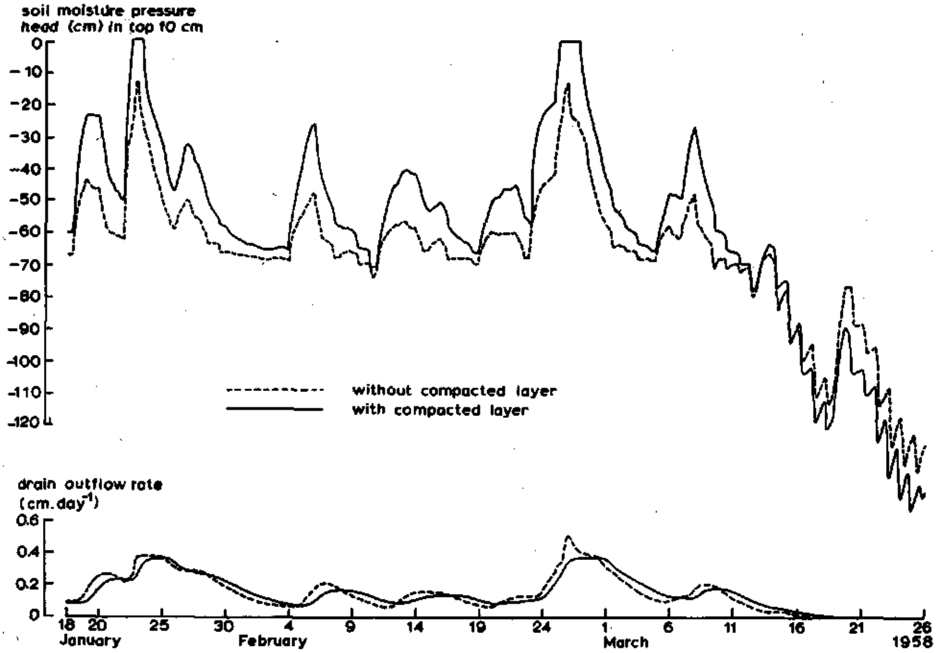


Fig. 12. Effect of a compacted layer between 20 and 30 cm depth on the moisture condition of the topsoil and the drain outflow rate.

moisture pressure head in the top 10 cm of a loam soil during the extremely wet autumn of 1974 for three drain spacings. It shows how the pressure head varies from day to day. Although the soil with the highest drain intensity (0.037 or about 2.5 times normal) was less wet than the others, drier conditions than those corresponding with a pressure head of −80 cm were not observed, while a head of −90 cm is required for the harvesting of potatoes.

Another example, here reproduced in Fig. 11, shows the soil moisture pressure heads as having occurred during the autumn of 1974 in the top layer of three soils, all drained at 100 cm depth with an extremely narrow spacing. The soils used are a loam, a sand and a soil consisting of 40 cm loam on sand (in Dutch: plaatgrond). In wet periods the loam is wettest and the sand the driest soil, the loam on sand has an intermediate moisture content. In dry periods during this wet autumn, the loam on sand is in most cases the driest and the sand often the wettest soil. The differences between the drain outflow graphs of loam and sand are as is to be expected when comparing soils with low and with high moisture storage capacities. Although the groundwater table in the loam on sand never did rise into the loam layer, the drain outflow nevertheless nearly behaved as that of a loam soil.

The last example, Fig. 12, shows the effect of a dense soil layer in winter and spring. During rainy periods the soil with a compacted layer is wetter than the one without it. In dry periods in March the former is drier than the latter because under the given conditions the compacted layer is impeding capillary rise.

4 Comparison of methods

4.1 Example characteristics

With the aid of the methods mentioned in the Chapters 2 and 3, it is possible to predict the effect of changes in soil properties or drainage. A practical example is chosen to illustrate the results obtained with different methods to predict the effects of ameloration.

A soil, LCS, consisting of 40 cm loam on 20 cm heavy clay on sand, drained at 80 cm depth is said to reach the state of workability too late in spring.

Two ameliorations are considered: increasing the drain depth to 110 cm below surface and improvement of the clay layer by subsoiling. It is asked to forecast the effect of each and of a combination of both ameliorations.

The answer will be given:

- with the sole use of steady state considerations (Section 4.2);
- with a pseudo-steady state method (Section 4.3);
- with a numerical dynamic model using standardized weather data (Section 4.4);
- with an analog model using real weather data as input (Section 4.5).

The following assumptions are made. The loam and the clay have an exponential $k(\psi)$ relation, see Eq. (3). For the loam $k_0 = 3\ \mathrm{cm \cdot day^{-1}}$; $\alpha = 0.03\ \mathrm{cm^{-1}}$; for the clay $k_0 = 0.3\ \mathrm{cm \cdot day^{-1}}$ and $\alpha = 0.015\ \mathrm{cm^{-1}}$. The sandy soil is thought to be always in static equilibrium with the groundwater table. So in the sand at any time $\psi(h)$ equals the height h above the groundwater table. The moisture characteristics of loam, clay and sand are as shown in Fig. 13.

With regard to subsoiling, the clay layer then gets the same properties as the loam, its thickness does not change, so the LCS soil changes into a LS soil consisting of 60 cm loam on sand. The drainage is ideal: the groundwater table depth equals drain depth during drain discharge. Except for this, no control of the groundwater table exists, so it may fall below drain depth. The soil is taken to be workable for seedbed preparation when the soil moisture pressure head at surface is -150 cm.

4.2 Steady state considerations

To calculate the effect of drainage and soil improvement on moisture content of a soil in wet periods with steady state considerations, one has to choose a certain constant precipitation rate. In Fig. 14 a downward flux of $0.5\ \mathrm{cm \cdot day^{-1}}$ has been chosen. In the LCS soil this leads to very large gradients in the clay layer, which has a saturated conductivity of only $0.3\ \mathrm{cm \cdot day^{-1}}$.

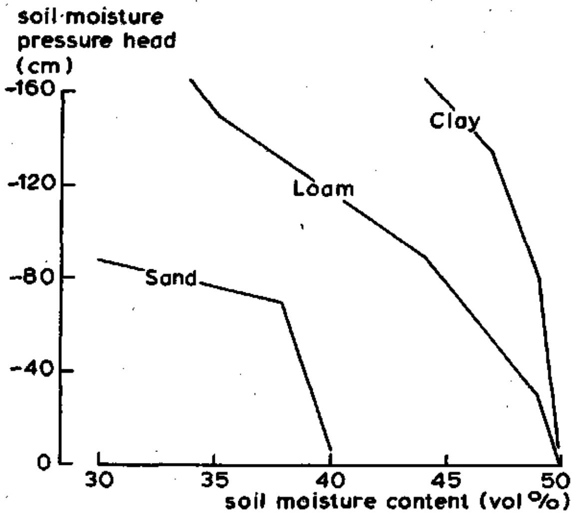


Fig. 13. Moisture characteristics of the example soils L (loam), C (clay) and S (sand).

In Table 2 the calculated pressure heads at the soil surface are given for three fluxes. Both ameliorations, deeper drainage and soil improvement have a favourable effect on the moisture conditions, as with these ameliorations the top soil is less wet than without them. The effect of soil improvement exceeds that of deeper drainage except for the flux of $-0.2\ \mathrm{cm \cdot day^{-1}}$. Especially during very high rainfall rates ($1.0\ \mathrm{cm \cdot day^{-1}}$) the effect of soil improvement is paramount.

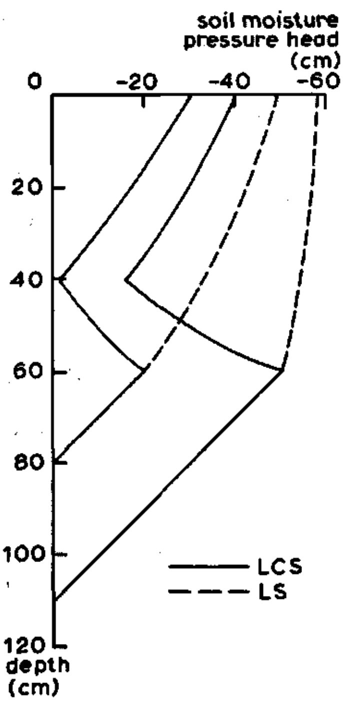


Fig. 14. Soil moisture pressure head profiles in the LCS and the LS soil, drained at 80 and 110 cm below surface, at a steady downward flux of $0.5\ \mathrm{cm \cdot day^{-1}}$.

Table 2. Soil moisture pressure head at the soil surface (ψ_s in cm) for the LCS soil and the LS soil drained at 80 and 110 cm depth respectively for three downward fluxes.

Downward flux ($cm \cdot day^{-1}$)	Soil, respectively drain depth (cm)			
	LCS		LS	
	80	110	80	110
0.2	−53.1	−68.3	−64.1	−79.3
0.5	−30.0	−40.1	−49.0	−57.9
1.0	+3.6	−10.6	−33.2	−38.5

Calculation of the effect of the two ameliorations on the timeliness of field operations is not possible with steady state considerations. Only an approximation can be made. In Fig. 15 steady state pressure head profiles are given as calculated under the assumptions that at the surface $\psi = -150$ cm (workability) and that groundwater depth equals drain depth. The latter assumption is not likely to be true, but every other assumption with regard to groundwater depth is incorrect too.

To reach $\psi = -150$ cm at the surface in the LS soil a higher evaporation rate is required then in the LCS soil. This means that the LS soil will be workable later in spring than the LCS soil, so the effect of soil improvement seems to be negative. On the other hand the LCS soil is likely to be wetter than the LS soil at the beginning of an evaporative period. Which of the two effects is prevailing cannot be concluded from steady state considerations.

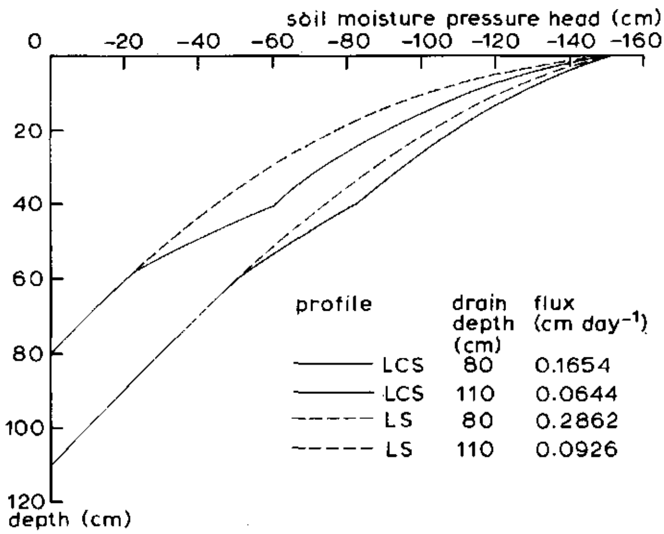


Fig. 15. Steady state pressure head profiles for LCS and LS soil, calculated for a soil moisture pressure head of −150 cm at the surface and groundwater depth equalling drain depth at 80 and 110 cm respectively.

The conclusion is that deeper drainage will work very favourable on the timeliness of field operations. It cannot be said whether soil improvement will cause a negative or positive effect.

4.3 Pseudo-steady state method

To apply the pseudo-steady state method the total amounts of soil moisture have to be calculated for the initial condition, for the end situation and, in this case, for some situations in between. The basis for this calculation are the soil moisture pressure head profiles; for given soil properties these steady profiles are defined by two data. These can be pressure head values at two depths or a pressure head value at one depth and the flux.

The initial condition is fixed by $\psi = 0$ at drain depth and a flux of $-0.5 \text{ cm} \cdot \text{day}^{-1}$ (downward) as in Fig. 14. The following sequence of situations has been chosen: −0.5; −0.4; −0.3; −0.2; −0.1 and $0 \text{ cm} \cdot \text{day}^{-1}$, all combined with $\psi = 0$ at drain depth. Between these situations moisture is removed both by drainage and evaporation. Between the pressure head profile of $0 \text{ cm} \cdot \text{day}^{-1}$ (static equilibrium) and the final situation moisture loss is only caused by evaporation.

The choice of the end situation causes a problem. It makes sense to define the end situation by $\psi_s = -150$ cm at the soil surface (workability requirement) and a flux equalling evaporation rate E_0. However, in some parts of this profile the soil can be wetter than in the initial condition. This is shown in Fig. 16; the curve of $+0.2 \text{ cm} \cdot \text{day}^{-1}$ (upward flux) is in equilibrium with a groundwater depth of 73 cm below surface in the LCS soil.

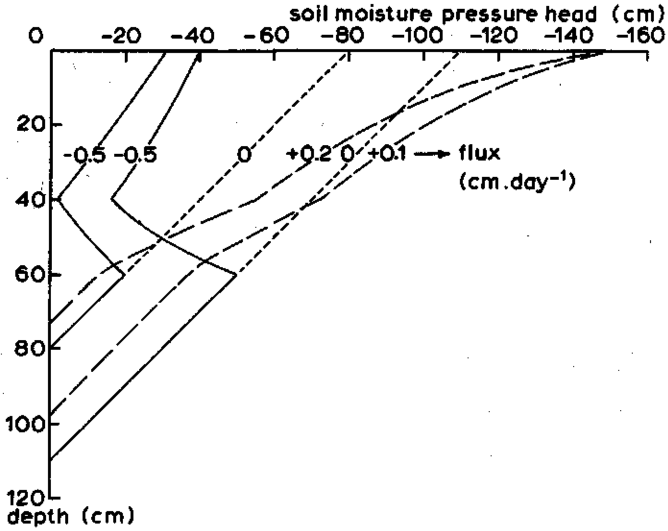


Fig. 16. Pressure head profiles in LCS soil with fluxes of −0.5 and $0 \text{ cm} \cdot \text{day}^{-1}$ at two drain depths (80 and 110 cm below surface) and fluxes +0.1 and $+0.2 \text{ cm} \cdot \text{day}^{-1}$ with a soil moisture pressure head of −150 cm at the soil surface.

Application of this curve assumes an increase in soil moisture in the soil deeper than 50 cm, which certainly is incorrect. To avoid this inconsistency, the [$v = \bar{v}_0$; $\psi_s = -150$ cm]-curve is used to the depth where it crosses the [$v = 0$; $\psi_s = 0$]-curve. For deeper layers the static equilibrium curve is used.

The pressure head profiles are to be translated into moisture content profiles, after which the difference in amount of moisture between these moisture stages is found by determination of the surface area between the curves. Fig. 17 gives an example of these profiles in the LS soil. In Table 3 the differences in amounts of moisture between the seven profiles are given.

These amounts are removed by drainage and evaporation. The duration of extraction is found by dividing the amounts of moisture by the total extraction rate. The total duration is the time required to reach a pressure head of -150 cm at the surface with an evaporation rate of $0.1\ \mathrm{cm \cdot day^{-1}}$, starting with an initial condition of equilibrium at a precipitation rate of $0.5\ \mathrm{cm \cdot day^{-1}}$.

The calculations have been carried out for both soils, two drain depths and two evaporation rates. The result is given in Table 4.

From this table conclusions can be drawn about the effects of drain depth and

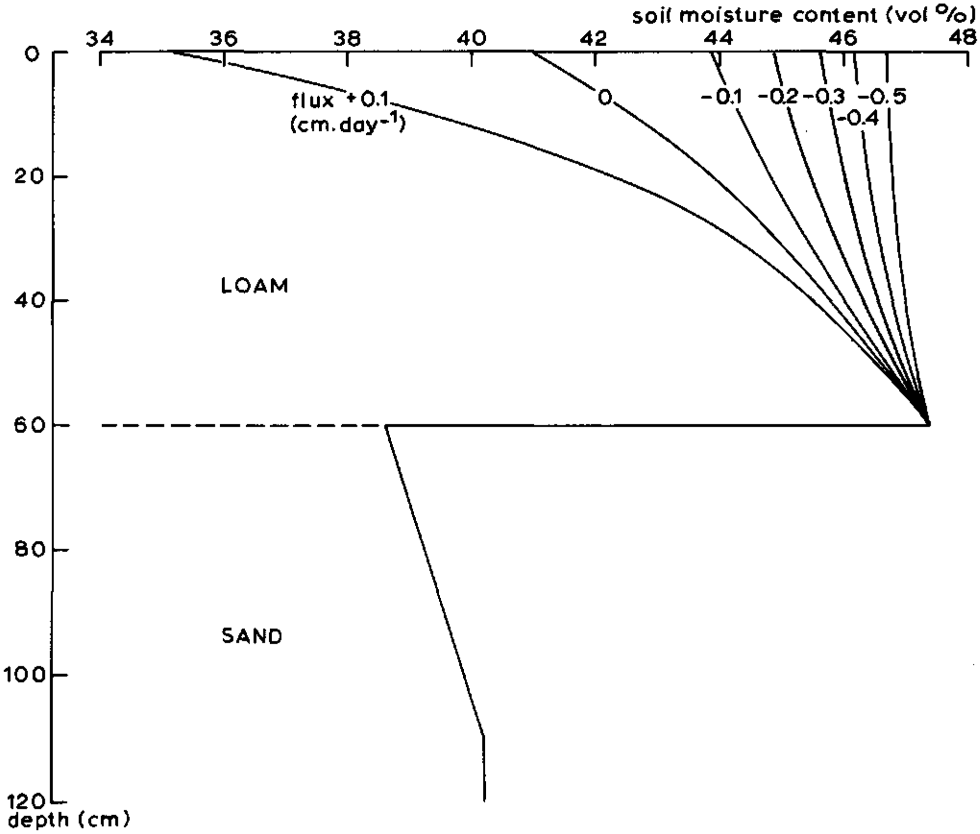


Fig. 17. Steady state moisture profiles in loam on sand soil, LS, drained at 110 cm depth.

Table 3. Differences in amount of moisture between seven steady state soil moisture profiles in the loam on sand (LS) soil drained at 110 cm, as well as mean extraction rates and the duration moisture extraction takes (see Fig. 19).

Steady state flux ($cm \cdot day^{-1}$)	Difference in amount of moisture between this steady state and its forerunner (cm)	Extraction rates by			Duration of extraction (day)
		drainage ($cm \cdot day^{-1}$)	evaporation ($cm \cdot day^{-1}$)	total ($cm \cdot day^{-1}$)	
−0.5 to −0.4	0.170	0.45	0.1	0.55	0.31
−0.4 to −0.3	0.196	0.35	0.1	0.45	0.43
−0.3 to −0.2	0.229	0.25	0.1	0.35	0.66
−0.2 to −0.1	0.283	0.15	0.1	0.25	1.13
−0.1 to 0	0.506	0.05	0.1	0.15	3.37
0 to +0.1	0.781	0	0.1	0.10	7.81
Total	2.165				13.71

soil improvement on the timeliness of field operations. It is clear that deeper drainage has a favourable effect: at a low evaporation rate it about halves the time to reach workability. With a high evaporation rate the effect is less but still positive. Soil improvement has a negative effect at a low evaporation rate, while it is positive at the high evaporation rate; although only small at a drain depth of 80 cm. Combination of deeper drainage and soil improvement is very profitable for both evaporation rates.

The conclusion is that it should be recommended to execute deeper drainage or deeper drainage combined with soil improvement but certainly not soil improvement only.

As regards the earlier reaching of workability conditions, this application of the pseudo-steady state method confirms the conclusion of the steady state method with respect to deeper drainage. As regards soil improvement it shows that this can work out positively or negatively. It gives quantitative information, although it is difficult to select the evaporation rate to be used in the calculations. In March and April, days with 0.1 or 0.2 cm evaporation do not seldom occur, but they are

Table 4. Number of days needed to reach workability in spring ($\psi = -150$ cm), calculated by the pseudo-steady state method. An initial situation of equilibrium with a constant precipitation rate of 0.5 $cm \cdot day^{-1}$ is followed by a dry period with evaporation as indicated.

Drain depth (cm)	Soil, respectively evaporation rate ($cm \cdot day^{-1}$)			
	LCS 0.1	LS 0.1	LCS 0.2	LS 0.2
80	26.5	29.4	10.0	9.4
110	13.1	13.7	7.8	5.2

alternating with rainy days. The effect of such changes is difficult to predict and the pseudo-steady state method gives no opportunity for more refined calculations.

4.4 Dynamic model with standardized weather conditions

A dynamic model has been applied with the same standardized weather conditions as were used in the application of the pseudo-steady method: an initial situation of equilibrium at constant precipitation rate of 0.5 $cm \cdot day^{-1}$, followed by a period with evaporation rates of 0.1 and 0.2 $cm \cdot day^{-1}$.

The model used was the numerical model described by Wind & van Doorne (1975). Because the original model can only work with uniform soils it has been modified for a three-layer soil. This modification was necessary in order to calculate the flux v between the upper layer (with conductivity k_1, saturated conductivity k_0 and coefficient α) and the lower layer (with conductivity k_2^*, saturated conductivity k_0^* and coefficient α^*). It was assumed that v and ψ are the same just above and below the boundary between the layers of different composition. When the conductivity at the boundary is called k_b respectively k_b^*, there are 4 equations and 4 unknown values (v, ψ, k_b and k_b^*):

$$\psi = \frac{1}{\alpha} \ln \frac{k_b}{k_0} = \frac{1}{\alpha^*} \ln \frac{k_b^*}{k_0^*} \tag{14}$$

$$v = \frac{k_b - k_1\sqrt{a}}{\sqrt{a}-1} = \frac{k_2^* - k_b^*\sqrt{a^*}}{\sqrt{a^*}-1} \tag{15}$$

where $a = e^{\alpha\Delta z}$ and $a^* = e^{\alpha^*\Delta z}$. From this set of equations the flux v through the boundary can be calculated. For the computations, the same soil properties as in the applications of the pseudo-steady state method were used.

In Fig. 18 the results are given for the loam on sand soil (LS) drained at 110 cm depth at a constant evaporation of 0.1 $cm \cdot day^{-1}$. The striking differences with Fig. 17 will be discussed later. In Table 5 the time between initial situation and the moment that the pressure head at surface equals −150 cm is given.

The conclusions to be drawn from this table are not entirely identical with those from Table 4. Deeper drainage has a very good effect indeed, but it is smaller than follows from the pseudo-steady calculation. As regards the effect of soil improvement, this only works negatively for the 80 cm drain depth and the low evaporation rate. Although the positive effects of soil improvement are small, Table 5 gives somewhat more doubt with regard to the effect of this amelioration than does the pseudo-steady state calculation.

The largest difference between Tables 4 and 5 is the absolute value of the extraction duration. The dynamic simulation predicts much longer durations than the pseudo-steady state calculations. A priori it was expected that dynamic simulation would give smaller durations, because of a higher extraction rate from the top layers, than is assumed by the pseudo-steady state calculation with its constant fluxes. The reverse turned out to be true. The amount of moisture extracted from deeper layers according to dynamic simulation, is larger than is

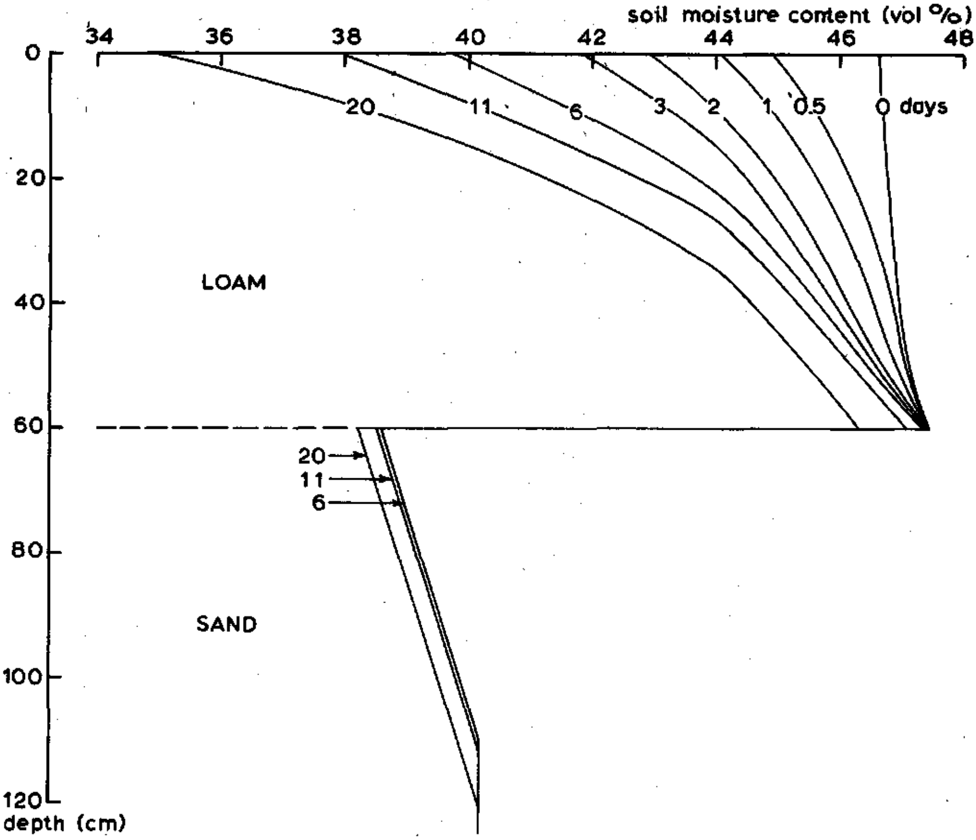


Fig. 18. Moisture profiles in LS soil, drained at 110 cm, as simulated with a dynamic model. The numbers in the figure give the number of days after a constant rain rate of 0.5 cm · day^{-1} did stop. Evaporation rate 0.1 cm · day^{-1}.

calculated with pseudo-steady method. This is shown in Fig. 19 where dynamic and pseudo-steady state moisture profiles are compared. At any time up to 5.9 days the top soil moisture status dynamically simulated is drier than calculated with the pseudo-steady state method. Between 5.9 and 13.7 days this situation changes. On the last mentioned date the pseudo-steady state method calculates a drier top soil than dynamic simulation does. The reason for this behaviour is the assumption in the first

Table 5. Time in days between the initial situation with a constant 0.5 cm · day^{-1} rain rate and the moment that at the surface $\psi = -150$ cm, as calculated with a dynamic model.

Drain depth (cm)	Soil, respectively evaporation rate (cm · day^{-1})			
	LCS 0.1	LS 0.1	LCS 0.2	LS 0.2
80	33.8	37.1	14.0	12.6
110	21.6	19.8	9.4	7.0

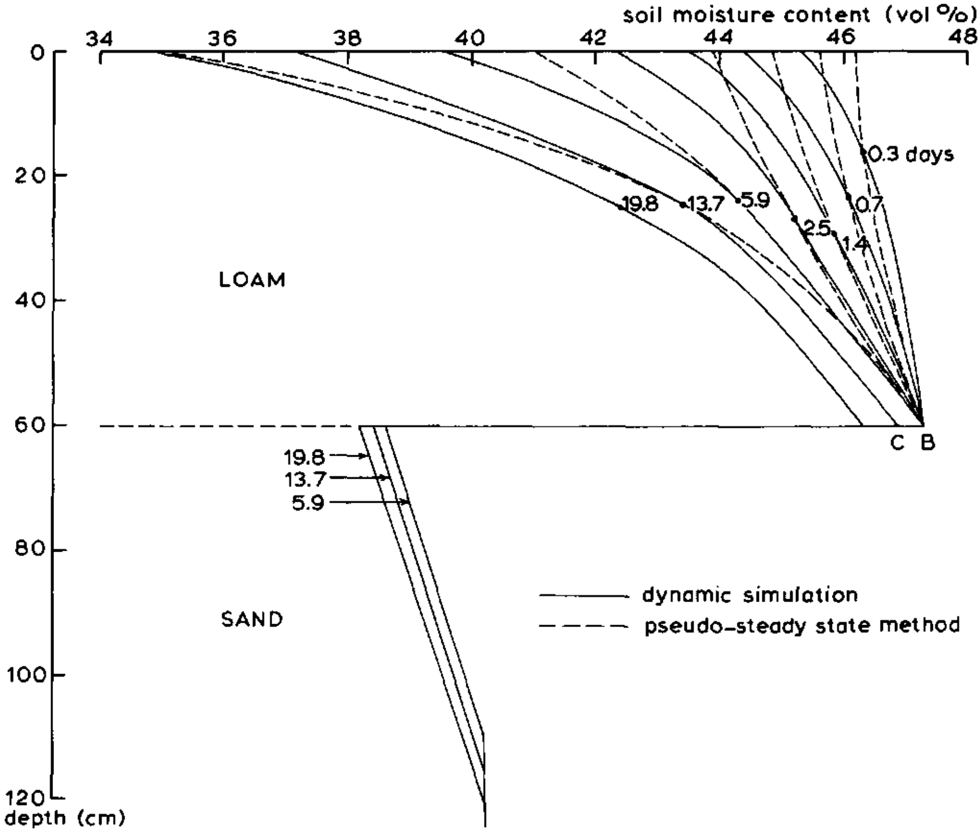


Fig. 19. Comparison of moisture profiles in LS soil, drained at 110 cm, calculated with dynamic simulation and the pseudo-steady state method for the same days after a rain period of $0.5 \text{ cm} \cdot \text{day}^{-1}$ did stop, given as numbers in the figure. These days correspond with those mentioned in Table 3.

method of a steady flux, in this case $0.1 \text{ cm} \cdot \text{day}^{-1}$, which leads to a high moisture content at 60 cm depth when at surface $\psi = -150$ cm is maintained. In reality, and the dynamic simulation pretends to represent reality, the flux decreases from $0.1 \text{ cm} \cdot \text{day}^{-1}$ at the surface to zero at a certain depth, thus causing a lower moisture content at 60 cm depth, see the points B and C in Fig. 19.

In Table 6 the observed fluxes are given. In the topsoil they are larger than those used in steady state calculation at any time up to day 13.7; then the flux is suddenly smaller than the assumed value of $0.1 \text{ cm} \cdot \text{day}^{-1}$. In pseudo-steady state calculations there is no reason to choose another value for the flux than the one equalling precipitation or evaporation rate, but this causes an incorrect gradient in the suction profile. Therefore the pseudo-steady state method is not very fit to calculate absolute values as duration of drying or amounts of available moisture.

As regards the comparison of the two amelioration methods, the results of the pseudo-steady state and the dynamical calculation differ only slightly. The schematic choice of a constant evaporation rate, however, leaves some reason for doubt about the conclusions.

Table 6. Fluxes in cm · day^{-1} as determined by the dynamic simulation of the moisture status of LS soil, drained at 110 cm with an evaporation rate of 0.1 cm · day^{-1} at selected days and depths. The steady state fluxes, as used in the pseudo-steady calculation are also given.

Depth (cm)	Time (days)								
	0	0.3	0.7	1.4	2.5	5.9	13.7	19.8	30.0
10	−0.50	−0.120	−0.048	−0.014	+0.007	+0.054	+0.075	+0.075	+0.074
20	−0.50	−0.268	−0.180	−0.090	−0.040	+0.022	+0.056	+0.057	+0.058
30	−0.50	−0.422	−0.286	−0.166	−0.075	+0.009	+0.041	+0.042	+0.044
40	−0.50	−0.458	−0.366	−0.220	−0.100	+0.001	+0.032	+0.034	+0.031
50	−0.50	−0.483	−0.398	−0.247	−0.115	−0.003	+0.024	+0.026	+0.024
60	−0.50	−0.490	−0.437	−0.269	−0.123	−0.004	+0.018	+0.018	+0.018
Steady	−0.50	−0.400	−0.300	−0.200	−0.100	0	+0.100	—	—

4.5 Analog simulation with real weather data

With the electronic analog model ELAN described by Wind & Mazee (1979) a simulation was made over 6 springs between 1970 and 1975. The two soils, LCS and LS, were taken to have drain depths at 80 respectively 110 cm below surface. The soil properties brought into the model were practically the same as in the earlier calculations. Precipitation and evaporation data were obtained from the Royal Meteorological Institute's station at De Bilt. The evaporation data, available per month, were distributed over the days according to the known radiation data. For every day, lasting 2 seconds in the model, there were 5 readings of the paper tape reader. Rainfall was distributed evenly over these readings; evaporation was situated exclusively in the third reading. This causes the oscillations in the curves of Fig. 20. This figure gives an example of the simulations, which began with an initial condition of a constant downward flux of 0.5 cm · day^{-1} on February 1, 1972.

Initially the LCS soil clearly is wetter than the LS soil with the same drain depth. Near the middle of February this changes and afterwards the LCS soil remains drier than the LS soil for both drain depths. This picture was repeated in all the 6 years simulated. So it is not surprising that, as shown in Table 7, the workability of LCS soil was much better than that of LS soil. This table gives the number of workable days in February, March and April for two criteria: mean soil moisture pressure head in the top 10 cm of respectively −100 and −150 cm.

The conclusion from the former studies that deeper drainage is very profitable for workability, is confirmed. As regards soil improvement the conclusion can be very clear: not advisable.

The simulation with real weather data also allows us to draw quantitative conclusions. For example the mean sowing date can be determined from recordings like Fig. 20. One has to know the soil moisture pressure head at which field operations can be carried out and the number of days required for planting a crop. Let the critical ψ's be −100 cm for sowing spring grains and −150 cm for planting potatoes, while both crops need 5 days for field operations in spring.

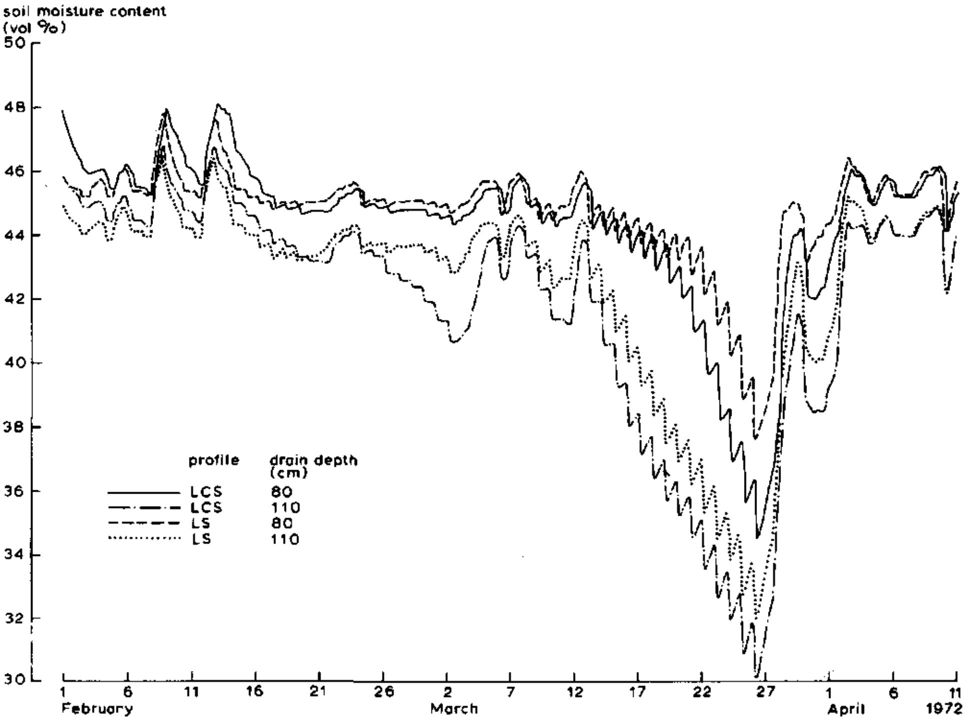


Fig. 20. Moisture content θ (volume %) during the spring of 1972 in the top 10 cm in LS and LCS soil, drained at 80 respectively 110 cm depth, as simulated by the electronic analog ELAN.

Then the mean planting date can be read from the recordings. The data are averaged over 6 years and given in Table 8.

By increasing the drain depth from 80 to 110 cm, planting can be achieved about one month earlier. Soil 'improvement' causes a delay of about half a month.

The question arises whether this soil improvement has any favourable effects. If

Table 7. Mean number of workable days per year for two soils (LCS and LS) and two drain depths in the years 1970 through 1975. Workability defined by soil moisture pressure heads of −100 respectively −150 cm in the top 10 cm in February, March and April.

Month	Drain depth (cm)	Workability criterion ψ, respectively soil			
		−100 cm		−150 cm	
		LCS	LS	LCS	LS
February	80	0.1	0	0	0
	110	6.6	1.4	0	0
March	80	5.8	2.2	0.2	0
	110	23.3	10.2	3.7	1.0
April	80	13.9	10.3	7.3	4.8
	110	20.8	17.8	13.2	8.0

Table 8. Mean planting date of spring grains and potatoes in two soils (LCS and LS) and two drain depths during the years 1970 through 1975. Dates determined under the assumptions given in the text.

Drain depth (cm)	Crop, respectively soil			
	Spring grain		potatoes	
	LCS	LS	LCS	LS
80	March 31	April 15	May 8	May 13
110	February 25	March 14	April 10	April 25

it has, it should be during periods with much rain, considerably more rain than is falling in spring periods. As an example a simulation run was made with weather data from the very wet autumn of 1974. The number of days with a very wet soil is given in Table 9.

During this period with rain rates clearly exceeding the k_0 value of $0.3\ \text{cm} \cdot \text{day}^{-1}$ of the clay layer, removal of this layer has a good effect, even better than deeper drainage has.

4.6 Discussion

During the last decades soil science has rapidly developed. In every stage of development practical investigators have tried to apply the soil physical theory to field problems. They wanted to explain the results of experiments and to predict the results of technical operations. In this chapter it has been shown which possibilities the application of soil science in four stages of development could have given for the solution of such a practical problem: Which is the effect of deeper drainage and the removal of a clay pan on the timelinesss of field operations in spring?

The methods used were (1) steady state considerations, (2) pseudo-steady state calculations, (3) dynamic simulation with standardized weather data and (4) dynamic simulation with real weather data.

With regard to deeper drainage, all methods predict a favourable effect on workability. Steady state considerations are scarcely able to find quantitative

Table 9. Number of days with an air content in the top 10 cm of less then 2 vol. % during October and November 1974 in two soils for two drain depths.

Drain depth (cm)	Soil	
	LCS	LS
80	15.2	7.0
110	9.0	4.6

effects. With the second and third method some indication is found on the magnitude of the effect, but there are fairly large differences between the results of the methods. This stresses the necessity to be careful in applying the pseudo-steady state method. Only simulation with real weather data can give a really quantitative prediction of the effect.

As far as subsoiling is concerned, there is much difference in the conclusions. With the first method hardly any conclusions can be drawn; the second and third method are showing varying effects depending on drainage and weather conditions. Both are leaving some doubt. The fourth method gives a clear conclusion: removal of the clay pan is not beneficial to workability in spring.

The earlier methods can give only poor quantitative information; the conclusions can even be wrong. The simulation with real weather data gives the most information. Its results should be compared with field observations to see whether this information is correct. There certainly will be differences, e.g. the method does not include the effects of hysteresis, nor is allowance made of soil properties varying through the year.

The development of soil science, combined with the possibility of its application by dynamic models, should have influence on the organization of agricultural research. Field experiments can be replaced partly by model investigations. Experimental fields can be set up for a simpler performance or for a shorter duration. The observations to be made will differ from those formerly made because they have to supply data for model application and are to be used to check model results.

5 Applications

5.1 General

The described models simulate moisture conditions in a number of layers, surface run-off and drain outflow. The electronic analog and numerical models can be used in an inductive way to derive soil properties from field observations. They can be applied for studies in which output data are important: effect of drainage, tillage, soil improvement, etc.

A number of limitations was treated in Section 1.3. Another important limitation is that the $\psi(\theta)$ and $k(\psi)$ relationship of the soil must be known. Especially for the $k(\psi)$ relationship few reliable data are available.

5.2 Checking the models

The ultimate check of a model is the comparison between simulated and observed field data over a period not used for calibration. If they do not agree, the model is incorrect. Mostly there is some doubt about the observed moisture contents and about the laboratory determined $k(\psi)$ and $\psi(\theta)$ relationships. By changing these relationships the simulated values often can be brought to approach the observed values. So in most cases it is very difficult to judge whether the model is wrong or the parameters used were incorrect. Another practical problem is precipitation, as there can be a difference between the amount of rainfall at the site of moisture sampling and at the site of the rain gauge. Even the latter can differ from the real rainfall. Moreover, the distribution over the day differs from the distribution which can be applied in the model, and is often unknown.

The most direct check was made on the hydraulic analog where the simulated numbers of workable days were compared with field observations by Hokke & Tanis (1978) over 23 years, see Fig. 21. It shows a good agreement between observed and calculated data. The largest differences, in 1963 and 1964, may have been caused by the fact that the real drain depth in the polder 'Hoeksche Waard' was perhaps less than the 100 cm used in the model. For those two years the effect of drain depth was very large.

A comparison of the results obtained with different models is very well possible. Wind (1972) compared hydraulic model data with those from a simple numerical calculation. Wind (1976) compared hydraulic model data with data computed by van Keulen & van Beek's (1971) numerical model. Fig. 22 shows part of this comparison, including more recent data calculated by the electronic analog. Wind

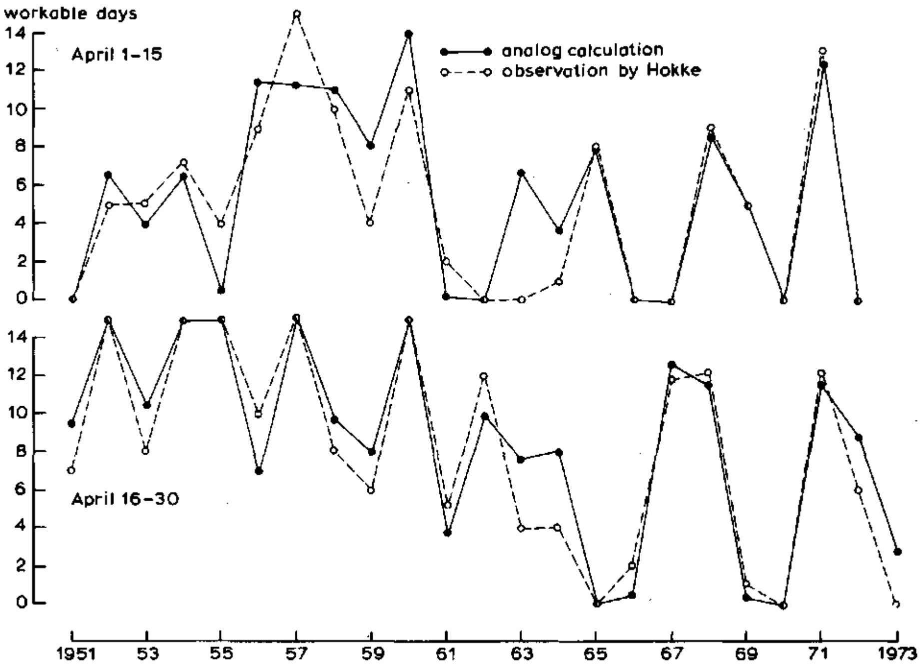


Fig. 21. Simulated and observed number of workable days in the Aprils of 1951 through 1973.

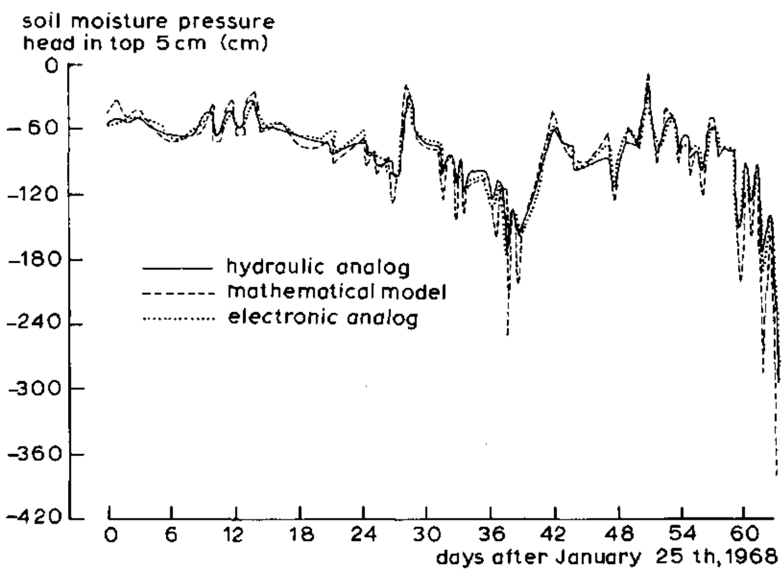


Fig. 22. Soil moisture pressure head in the top 5 cm of a loam soil in spring 1968, as simulated by the numerical model of van Keulen & van Beek (1971), the hydraulic analog (Wind, 1972) and the electronic analog ELAN.

& Mazee (1979) give comparisons of the electronic analog with Wind & van Doorne's (1975) numerical model FLOW.

All these comparisons showed excellent agreement between the results from the models used. This is not surprising because all the models are based on the same principle; they only differ in elaboration. The comparisons therefore did show that only minor mistakes were made in the elaboration, but they did not confirm the validity of the principle. The principle is a combination of Darcy's law and the continuity equation assuming that hysteresis can be neglected. If the models were to be shown incorrect, one or more of these laws or assumptions would also have to be wrong, and this is not to be presumed.

5.3 Inductive use

The purpose of application of these simulation models is to calculate moisture conditions from meteorological data. The soil properties should be known beforehand.

This is called the deductive application of models: field data are deduced from basic knowledge. Since sufficiently accurate data about soil properties often are not available, such a deductive use of simulation models has only restricted value.

If field data about soil moisture content are available, one can try to calibrate the model until its results fit these data. In this process one usually has to calibrate various soil parameters. The more soil parameters are unknown, the more difficult the matching problem will be. The following may serve as an example of such an inductive application. Wind (1976) obtained unsatisfactory results from a simulation run with the hydraulic analog, using for that particular soil values of k_0 and α valid for a comparable standard soil of Rijtema (1969).

According to the simulation, in a certain spring workable days did not occur although in reality that spring had very good workability conditions. Apparently the soil physical data used in the model were incorrect.

Reduction of the used value of k_0 to half its original value had hardly any effect and it was to be expected that this reduction in saturated conductivity had to go to unreasonably low values. Therefore different α-values were tried in the numerical model FLOW. The simulation results were compared with field observations in March 1973. With a certain value of α the model exactly described what had happened in reality.

Because the knowledge of soil physical properties is rather scanty, more attention should be given to this method of inductive use of models in combination with sensitivity analysis to determine the most important factors involved.

5.4 Workability in spring

Reeve & Fausey (1974) state that the most beneficial effect of drainage is early workability of the soil. That gives farmers the opportunity for early planting of crops, thus increasing the length of the growing season. Accurate data on the quantitative effect of drainage on workability are lacking, however.

The availability of a hydraulic analog opened the possibility to investigate this problem (Wind, 1976). The method of inductive use was applied to calibrate the main model specifications so that simulated moisture pressure heads agreed with those observed in 1973 (see Section 5.3).

This study was not only intended to investigate the effect of drainage on workability but also to produce data on the distribution of workable days. These were needed by another institute for labour studies about planting of potatoes. In cooperation with Perdok (1975) the workability limit for potato planting was fixed at a suction of 300 cm in the top 5 cm of the investigated loam soil.

Data of real precipitation and potential evaporation over 22 years between 1951 and 1973, were read from paper tape and used as input for the hydraulic model. Of each year 4 months were taken, beginning at January 1. As the time scale was 5 minutes representing one day, each simulation run lasted about 230 hours. As input 6 drain depths and 4 drain intensities were applied, but not in all combinations and not over all years. Nevertheless, the model had to work continuously for almost a year.

The investigated drain intensities were 0.0011, 0.0033, 0.008 and 0.015 day^{-1}. When drain depth is 100 cm below surface and midway between the drains groundwater depth is 50 cm below surface, these data correspond with drain outflow rates of 0.055, 0.165, 0.40 and 0.75 $cm \cdot day^{-1}$ respectively. The Netherlands drainage criterion of drain outflow under these conditions is 0.7 $cm \cdot day^{-1}$.

The result of the simulation experiment was that drain intensity had hardly any influence on workability in spring. The mentioned lowest intensity was already sufficient. The reason for this lack of influence is that drain outflow rates in spring are fairly small, because rain rates are low and evaporation is already important. So the groundwater table will only slightly exceed drain depth and the differences in groundwater depth for the mentioned drain intensities are small.

The effect of drain depth, on the contrary, was very large. Drain depths of 40, 80, 100, 150 and 200 cm below surface were investigated. The effect of drain depth differed from year to year; in very dry and in very wet springs the effect was small. In 10 of the 22 investigated years drain depth was very important with regard to the number of workable days.

The large effect of drain depth and the small influence of drain intensity lead to the supposition that a deep drainage system with low intensity can be very important for workability. As Ernst (pers. commun.) points out, such a drainage system is often present in practice. Part of excess rainfall is not discharged by the drain tiles but finds its way directly to lower lying ditches or canals.

This effect was investigated for the same soil with the electronic analog ELAN in which a double drainage system was made. A single drainage system at 90 cm depth with an outflow rate of 0.7 $cm \cdot day^{-1}$ at the normative groundwater depth of 50 cm below surface was compared with three double drainage systems. These were composed of a first system at 90 cm depth with an outflow rate of 0.6 $cm \cdot day^{-1}$, and an additional system with an outflow rate of 0.1 $cm \cdot day^{-1}$, both at the normative groundwater depth of 50 cm below surface. The additional drainage systems were situated at depths of 110, 130 and 150 cm below surface.

During February 1972 which had a rainfall surplus of about 24 mm, the results of the four drainage systems seemed to be fully identical. In March, with an

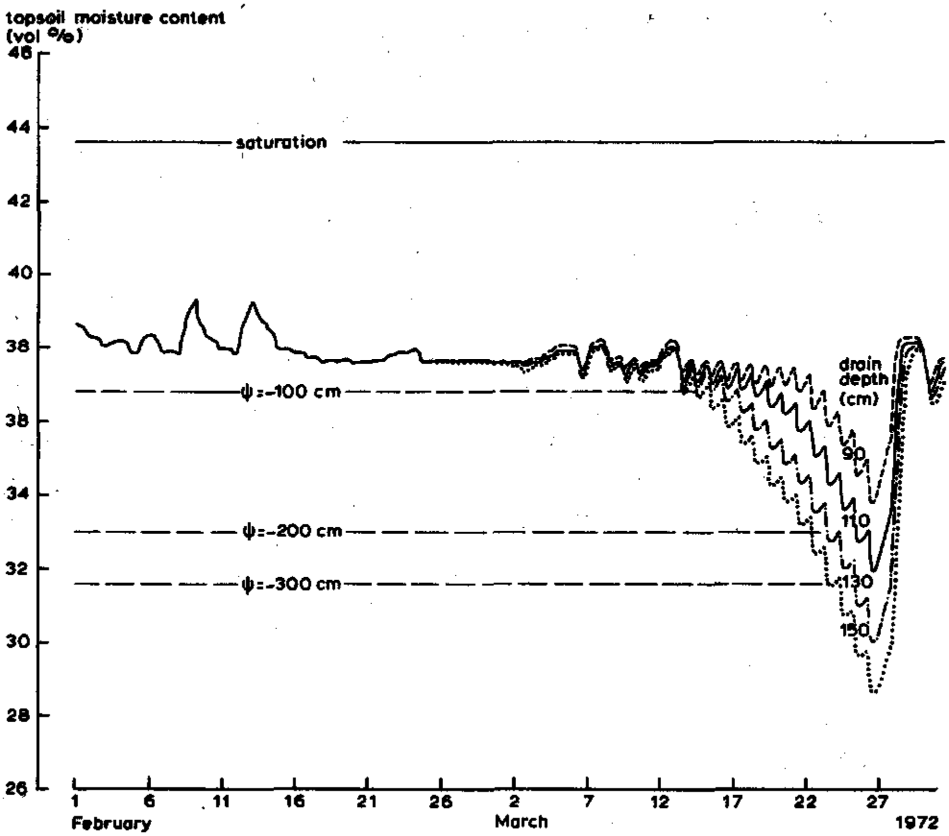


Fig. 23. Effect of double drainage systems on the moisture content in the top 10 cm of a loam soil. Four combinations are shown, each of them with a first system at 90 cm depth with an outflow rate of 0.6 cm · day^{-1} and a second system with an outflow rate of 0.1 cm · day^{-1} at a normative groundwater depth of 50 cm. The depth of the second systems, i.e. 90, 110, 130 and 150 cm, are indicated in the figure.

evaporation surplus, the effect of the additional low-intensity deeper drainage systems clearly appeared to be favourable for the soil moisture contents and hence for the number of workable days, see Fig. 23.

More important than the number of workable days is the first date of soil workability. This determines the date of planting and thus the length of growing season. After a certain date every day of delay causes an increasing depression in crop yield. How the dates of workability are influenced by drain depth is shown in Fig. 24. Deeper drainage results in earlier workability.

Feddes & van Wijk (1977) used the result of this study in combination with a planting date-yield relationship and a pseudo-steady state evapotranspiration model. With this integrated model approach they found that the optimum drain depth for this soil, a sandy clay-loam, ranges between 100 and 150 cm below surface, see Fig. 25.

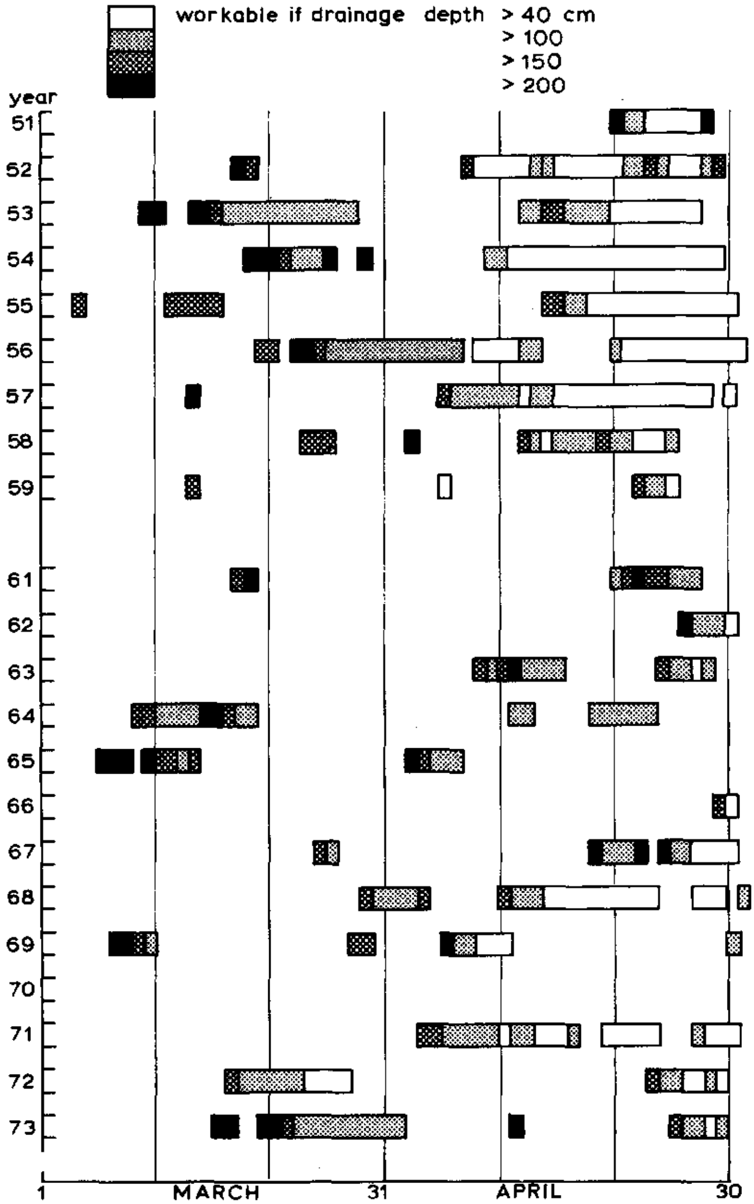


Fig. 24. Periods of workable soil calculated with the hydraulic analog for a loam soil for four drain depths in 22 years. Workability is defined here as a soil moisture pressure head in the top 5 cm being less than −300 cm.

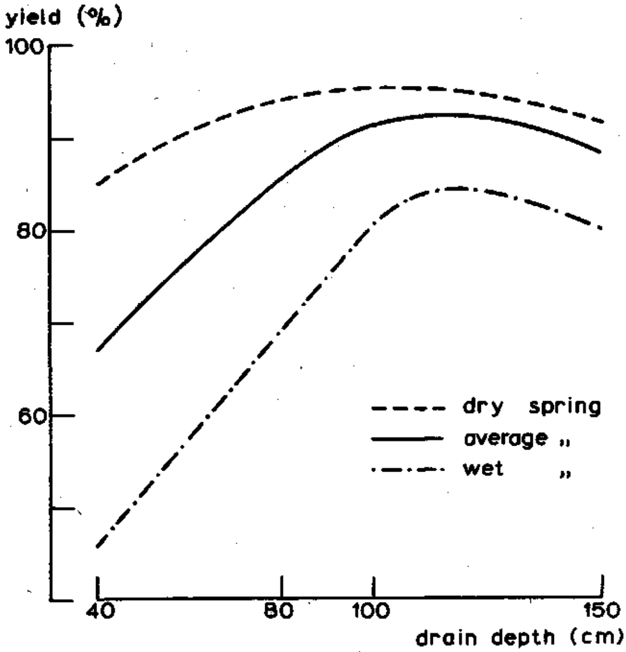


Fig. 25. Influence of drain depth on yield of summer cereals on a sandy clay loam for various types of spring conditions. After Feddes & van Wijk (1977).

5.5 Soil moisture content in dependence of drain depth and drain intensity

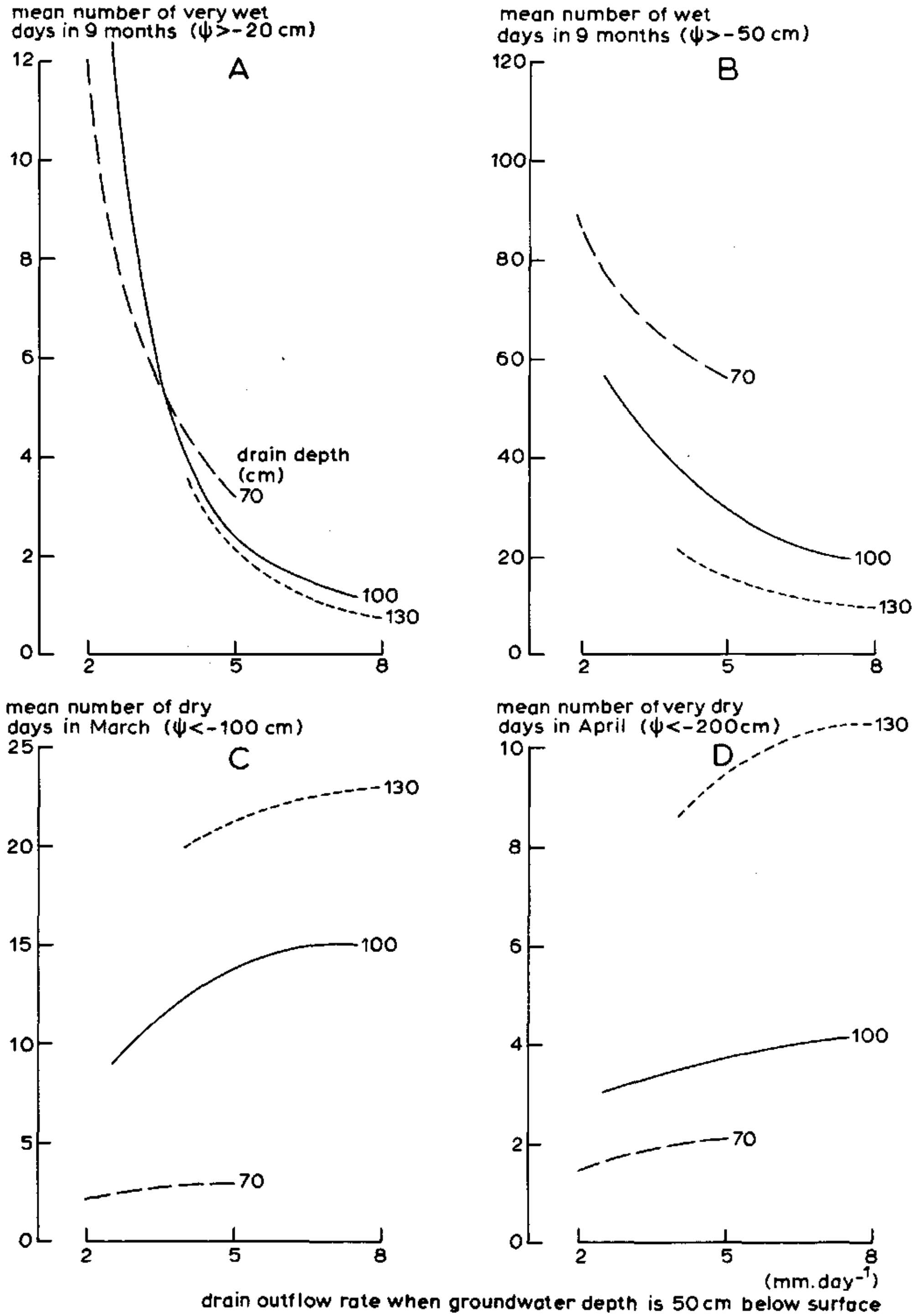
5.5.1 General

In Section 5.4 it was found that drain intensity above a certain low value had no influence on workability. Nevertheless drain intensity should be higher than that to serve another purpose of drainage: avoiding too wet conditions at other times. So to obtain low moisture contents in spring drain depth is important, but to avoid water logging in autumn, winter and early spring drain intensity should be high.

In order to see which combination of drain depth and intensity serves both drainage purposes best, an investigation was made with the electronic analog ELAN. Simulations were made with drain depths at 70, 100 and 130 cm below surface. With each depth three intensities were combined; they were chosen in such a way that drain outflow varied between 0.2 and 0.8 cm $\cdot$ day^{-1} when groundwater depth was 50 cm below surface. The simulations were made over 9 months beginning at September 1 in 35 years between 1941 and 1977.

5.5.2 Weather input and soil conditions

Precipitation and evaporation data of the Royal Netherlands Meteorological Institute's station in De Bilt were used. Precipitation data were observed as a daily total; in the model file this amount was distributed equally over the day. When evaporation was larger than rainfall the difference was applied in the middle of the day. Evaporation was calculated according to Penman over periods


mean number of very wet
days in 9 months (ψ>−20 cm)
A
drain depth
(cm)
70
100
130
mean number of wet
days in 9 months (ψ>−50 cm)
B
70
100
130
mean number of dry
days in March (ψ<−100 cm)
C
130
100
70
mean number of very dry
days in April (ψ<−200cm)
D
130
100
70
(mm.day⁻¹)
drain outflow rate when groundwater depth is 50 cm below surface

of one month. These data were multiplied with 0.8 and distributed over the days of the month, proportional to daily measured radiation data.

Only one, fictitious, soil was used; it had the following very simple soil properties: $\psi = 10\theta - 500$ and $k = 2e^{0.025\psi}$.

The initial condition at September 1 was always the same: a constant downward flux of 0.1 cm · day^{-1}. Surface run-off was set to occur when more than 1 cm water was ponded on the surface.

5.5.3 Results and discussion

Moisture content in the top 10 cm was recorded continuously. From this record were read:

- the number of very wet days, i.e. the top soil containing less than 2% air which means a soil moisture pressure head of more than −20 cm, Fig. 26A;
- the number of wet days, i.e. air content less than 5%, moisture pressure head more than −50 cm, Fig. 26B;
- the number of dry days with a moisture pressure head of less than −100 cm, Fig. 26C;
- the number of very dry days, with a moisture pressure head of less than −200 cm, Fig. 26D.

In the figures mentioned the drain intensity is expressed as the outflow rate (cm · day^{-1}) if groundwater depth is steady at 50 cm below surface. The Netherlands drainage criterion for arable land is recommending 0.7 cm · day^{-1} for this condition.

In Fig. 26A it can be seen that this leads to an average number of only one very wet day per winter (September to May). As the definition of a very wet day, used here, is a day with a soil moisture pressure head of more than −20 cm this agrees very well with Wesseling's (1969) result. From this figure it is clear that drain depth and drain intensity are nearly fully exchangeable as regards avoiding very wet conditions. At high outflow rates, deep drainage seems to be slightly better than a shallow one; for low outflow rates the reverse seems to be true. But the differences between the three drain depths are small as compared with those to be seen in the other parts of Fig. 26. Regarding the slope of the curves of Fig. 26A for outflow rates around 0.8 cm · day^{-1} it is not to be expected that larger outflow rates at normative groundwater depth will have much effect. So for this soil an outflow rate of 1.5 cm · day^{-1}, as is normative for sportsfields, has little sense if any. It appears that the norm of 0.7 cm · day^{-1} was well chosen, a decrease however, to 0.5 cm · day^{-1} (as originally chosen by Hooghoudt, 1937) would do

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Fig. 26. Effect of drain depth and drain intensity upon the number of days that certain reference levels of moisture conditions are exceeded. A, very wet condition, less than 2% air in the top 10 cm, soil moisture pressure head > −20 cm; B, wet condition, less than 5% air, soil moisture pressure head > −50 cm; C, dry soil, soil moisture pressure head < −100 cm; D, for spring conditions very dry soil with soil moisture pressure head < −200 cm.

not much harm. Below that value the number of very wet days increases considerably.

From Fig. 26B it can be seen that the number of wet days with a soil moisture pressure head of more than −50 cm, is about 10 times the number of very wet days with pressure heads of more than −20 cm. To avoid large numbers of wet days both drain depth and intensity are important but both factors are not exchangeable. An insufficient drain depth cannot be compensated by a large intensity.

Figs. 26C and 26D show that to obtain workable conditions drain depth is clearly far more important than drain intensity. Increase of drain depth from 70 to 100 cm causes a considerable increase in dry days (soil moisture pressure head less than −100 cm) in March, the period in which spring grains are mostly sown. For the number of very dry days (pressure head < -200 cm) in April when sugar beets and potatoes are planted, the difference between 70 and 100 cm drain depth is fairly small. This discrepancy between Figs. 26C and 26D is difficult to explain: models give results, not explanations.

The data given in this chapter do not allow to draw a conclusion with regard to optimal drain depth. For this purpose not only the number of workable days is required but also the dates of workability and the effect on the availability of moisture in summer (cf. Section 5.4 and especially Fig. 25).

In this section it has been shown that the electronic analog can handle very long time-series in an efficient way. As regards the effects of drain depth and intensity, it was demonstrated that the drier the reference value of soil moisture pressure head is chosen, the less is the influence of drain intensity.

Summary

The knowledge of the behaviour of water in soils has increased considerably in this century. What happens with rain water falling on the soil surface and which processes then are started is now fairly well known.

The processes involved have thoroughly been studied by many investigators all over the world, with the result that there exists a fairly good knowledge on surface run-off, infiltration, relationship between moisture content and energy status, relationship between moisture content and conductivity, flow processes in both the saturated and unsaturated zone and on the conduction of soil water to drainage systems.

The applicability of all this knowledge formerly was only partial and restricted. The most important item was that it gave soil technologists for their activities a theoretical basis in general terms. When computers became available, this opened the opportunity to actually calculate all these processes in their mutual connection. In this way the behaviour of water in soils now can be simulated. With the aid of numerical simulation models the effect of natural causes or human activities can be forecasted, not only in general terms but also quantitatively and from day to day.

This simulation proved to be so expensive in computer time, however, that it is not well possible to apply it to periods of several decades. The effects of soil technological measures, e.g. drainage, are different from year to year and from day to day, however. Depending on weather conditions a certain activity sometimes can have very large positive effects, in other periods no effect at all and in some years even negative effects. Therefore, in order to investigate the profits of soil technological measures a study over several decades is required. With the aid of analog models such long term investigations can be carried out at relatively low cost.

In this publication the development of some analog models is described, i.e. a hydraulic and an electronic analog. The latter is based upon the analogy between the integrated moisture flux equation and Ohm's law. The models are compared with numerical models and were checked with field observations. It is shown that long time series can easily and correctly be handled. Examples are given about the effects of drain depth and drain spacing on the moisture content of the topsoil. From these it appeared that drain spacing is important to avoid water logging conditions, but that it does not influence workability of the topsoil. To obtain early and good workability conditions for seedbed preparation, drain depth is more important.

It is demonstrated how soil physical knowledge can be applied to reach

conclusions in a soil technological problem. The problem given was to forecast the effects of soil improvement and drainage on workability of a layered soil. Steady state considerations, pseudo-steady calculations and dynamic model computations with standardized weather data, all did leave considerable doubt with regard to the amelioration method to be advised. Only a dynamic simulation with real weather data yielded clear conclusions.

Samenvatting

De kennis van het gedrag van water in grond is in deze eeuw aanzienlijk toegenomen. Tegenwoordig is goed bekend wat er gebeurt met regenwater dat op de grond valt en wat daarvan de invloed is. Een deel van het regenwater infiltreert in de grond, een ander deel verdwijnt door oppervlakte-afvoer. Het infiltrerende water doet het vochtgehalte van de bovengrond stijgen en verandert daarmee de potentiaal van het bodemvocht. Daardoor ontstaat een potentiaalgradiënt, die veroorzaakt dat water naar beneden gaat stromen. De stroomsnelheid wordt niet alleen beheerst door deze gradiënt, maar ook door het geleidingsvermogen van de grond voor water. Bekend is dat dit geleidingsvermogen afhangt van het vochtgehalte, evenals de wijze waarop zij samenhangen.

Bij de neerwaartse beweging bereikt het water de grens tussen onverzadigde en verzadigde zone. In de laatste kan het vochtgehalte niet meer toenemen en het geleidingsvermogen blijft daar constant. Door deze zone vloeit het water deels horizontaal, deels verticaal naar een ontwateringsstelsel. Verdamping doet de bovengrond uitdrogen; daardoor ontstaat een opwaartse waterstroming, vaak capillaire opstijging genoemd.

De processen die de stroming en berging van water in de grond beheersen zijn zorgvuldig bestudeerd door veel onderzoekers over de gehele wereld. Daardoor bestaat een goede kennis van oppervlakte-afvoer, infiltratie, de relatie tussen vochtgehalte en vochtpotentiaal, de relatie tussen vochtgehalte en geleidingsvermogen, stromingsprocessen in zowel de verzadigde als de onverzadigde zone en van de afvoer van water naar ontwateringsstelsels.

De toepasbaarheid van al deze kennis was vroeger slechts partieel en beperkt. Het belangrijkste was dat de cultuurtechnicus door deze kennis een theoretische basis in algemene termen had voor zijn praktische activiteiten. Toen computers beschikbaar kwamen ontstond de mogelijkheid om al deze processen in hun onderlinge samenhang door te rekenen. Zo kan nu het gedrag van water in de grond in modellen worden nagebootst, gesimuleerd. Met behulp van die simulatiemodellen kan het effect van natuurlijke gebeurtenissen of menselijke ingrepen worden voorspeld, niet slechts in algemene termen maar ook kwantitatief en van dag tot dag.

Deze simulatie bleek echter zoveel computertijd te kosten dat ze praktisch niet kan worden toegepast op lange perioden, zoals enige decennia. De effecten van cultuurtechnische maatregelen verschillen echter van jaar tot jaar en van dag tot dag. Afhankelijk van de weersomstandigheden kan een zekere activiteit, bijvoorbeeld drainage, een zeer gunstig effect hebben in bepaalde jaren, in andere perioden totaal geen effect en soms zelfs negatieve effecten. Om nu toch de baten van cultuurtechnische investeringen te kunnen waarderen is een studie over een lange reeks van jaren nodig. Met behulp van analoge modellen kunnen deze lange termijn onderzoekingen tegen lage kosten worden verricht.

In deze publikatie wordt de ontwikkeling van enige analoge modellen beschreven, namelijk een hydraulisch en een elektronisch analogon. Het laatste is gebaseerd op de overeenkomst tussen de geïntegreerde onverzadigde waterstromingsvergelijking en de wet van Ohm. De modellen zijn vergeleken met numerieke modellen en werden gecontroleerd met veldwaarnemingen. Getoond wordt dat lange tijdseries makkelijk en correct kunnen worden gehanteerd. Voorbeelden worden gegeven over de effecten van draindiepte en drainafstand op het vochtgehalte van de bovengrond. Daaruit blijkt dat de drainafstand zeer belangrijk is om zeer natte omstandigheden te vermijden maar dat deze weinig betekenis heeft voor de werkbaarheid van de grond. Om vroege en goede werkbare omstandigheden te verkrijgen is juist de draindiepte van grote betekenis.

Het effect van de methode waarmee bodemfysische kennis wordt toegepast om conclusies te bereiken met betrekking tot een cultuurtechnisch probleem wordt getoond. Het behandelde probleem was het voorspellen van de betekenis van grondverbetering en drainage voor de bewerkbaarheid van een gelaagde grond. Stationaire beschouwingen, pseudo-stationaire berekening en modelsimulatie met gestandaardiseerde weersgegevens lieten alle aanzienlijke twijfel bestaan over de te adviseren verbeteringsmethode. Alleen dynamische simulatie met werkelijk voorgekomen weersgegevens maakte duidelijke conclusies mogelijk.

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