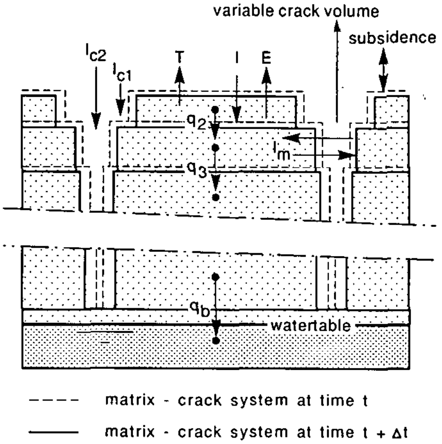

Figure 11.17 Concept for unsaturated water transport in cracking soils. I is the infiltration rate into the soil matrix, I_c is infiltration into cracks, I_m is the horizontal flux through the walls of the macropores, q is the Darcy Flux between two nodal points, and q_b is the bottom flux of the system (after Feddes et al. 1988)

various methods mentioned above. The common principle, however, is essentially the two-domain concept. The interaction between water in the two domains is also important. In some approaches, the total preferential flow is accumulated at the bottom of the macropores and is then added to the unsaturated flow at that depth (Bronswijk 1991).

A more general approach was suggested by Feddes et al. (1988), who linked preferential flow and matrix flow by extending the basic differential equation (Equation 11.49)

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)}\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - \frac{S(h)}{C(h)} + \frac{B(h)}{C(h)} \qquad (11.53)$$

where

B = source of soil water due to horizontal infiltration into the macropores, or a sink due to evaporation through the walls of the macropores

The resulting model is schematically illustrated in Figure 11.17. The quantification of the B-term in Equation 11.53, however, is difficult and requires a number of simplifications (Bronswijk 1991).

11.8 Simulation of Soil-Water Dynamics in Relation to Drainage

The design of drainage systems is usually based on criteria that are derived from steady-state or unsteady-state equations (Chapter 17). The underlying theories are mainly based on saturated flow to drains (Chapter 8), and do not consider the effects of drainage in the unsaturated zone, which is where the crops are rooted. The performance of drainage systems designed with those equations is subsequently tested in field trials or pilot areas (Chapter 12). Because of budget and time constraints, pilot areas may not represent the complete range of environmental conditions in a project area, and may not give an insight into the long-term sustainability of the drainage project.

Computer modelling can therefore be an important source of additional information, because many project conditions can be simulated quickly and cheaply for various time intervals. The principles and processes presented in Sections 11.3 to 11.7 can be used to predict soil-water dynamics and crop response. The interactions between all components involved are described by mathematical relationships, which can be combined in simulation models. One such simulation model is SWACROP (Kabat et al. 1992), which allows the user to evaluate the effect of different drainage strategies (i.e. criteria and designs) on water conditions in the unsaturated rootzone, and hence on crop production. After some introductory explanations (Sections 11.8.1 to 11.8.3), we shall illustrate the modelling approach with a number of examples from water-management and drainage practice (Section 11.8.4).

11.8.1 Simulation Models

'Simulation' is the use of models as tools to imitate the real behaviour of existing or hypothesized systems. Most important and interesting is the simulation of dynamic systems. Simulation models are usually realized in the form of computer programs and are therefore also referred to as 'computer models'.

A drainage simulation model for the unsaturated zone and crop production should, for example, be able to describe the effects of a specific drainage design on soil-water dynamics and related crop yields. Soil-water flow is also the governing factor in solute transport, and is thus responsible for changes in soil chemical status (e.g. plant nutrients and soil salinity; Chapter 15). Appropriate simulation models can predict the effects of different drainage designs on water and salt balances, which, in turn, relate to crop production.

The most complex simulation models are mathematical models that employ numerical techniques to solve differential equations (Section 11.8.2). Even if these models are mathematically and numerically correct, they need to be verified and calibrated against field data, and the required accuracy of input data needs to be assessed (Section 11.8.3).

11.8.2 Mathematical Models and Numerical Methods

Mathematical Models

In the previous sections, soil-water dynamics were cast in the form of mathematical expressions that describe the hydrological relationships within the system. The set of relevant partial differential equations, together with auxiliary conditions, define the mathematical model. The auxiliary conditions must describe the system's geometry, the system parameters, the boundary conditions and, in the case of transient flow, also the initial conditions.

If the governing equations and auxiliary conditions are simple, an exact analytical solution may be found. Otherwise, a numerical approximation is needed. Numerical simulation models are by far the most common ones.

Numerical Methods

At present, numerical approximations are possible for complex, compressible, non-homogeneous, and anisotropic flow regions having various boundary configurations.

Numerical methods are based on subdividing the flow region into finite segments bounded and represented by a series of nodal points at which a solution is sought. This point solution depends on the solutions of the surrounding segments, and also on an appropriate set of auxiliary conditions.

In recent years, a number of numerical methods have been introduced. The most appropriate methods for soil-water movement are 'finite-difference methods' and 'finite-element methods'.

To illustrate the use of finite-difference methods, we shall consider the case of one-dimensional unsaturated flow without sinks/sources (Equation 11.36). Let the flow depth be divided into equal intervals, ΔZ, and the time be similarly divided into time steps, Δt. The resulting two-dimensional grid is shown in Figure 11.18.

Equation 11.36 can now be expressed in finite difference form as

$$\frac{\theta_i^{j+1} - \theta_i^j}{\Delta_t} = \frac{1}{\Delta z}\left[K^j_{i+1/2}\left(\frac{h^j_{mi+1} - h^j_{mi}}{\Delta z} + 1\right) - K^j_{i-1/2}\left(\frac{h^j_{mi} - h^j_{mi-1}}{\Delta z} + 1\right)\right] \qquad (11.54)$$

where

i = index along the space coordinate
j = index along the time abscissa

Equation 11.54 represents the so-called forward difference scheme with an explicit linearization of the K(θ)-function.

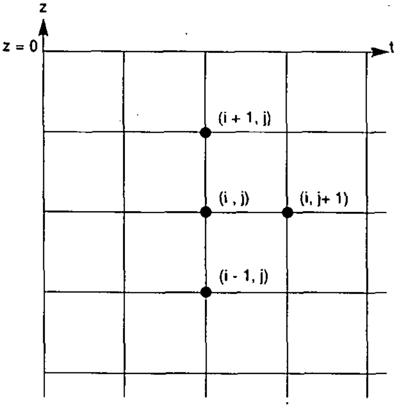

Figure 11.18 Bi-linear grid superimposed on the z-t-plane with the flow and time domain divided into equal intervals. The grid represents a forward finite difference scheme

Backward-difference schemes also exist. The resulting set of algebraic equations can be solved with special techniques such as linearization. The advantage of the finite-difference method is its simplicity and its efficiency in treating time derivatives. On the other hand, the method is rather incapable of dealing with complex geometries of flow regions, and has a few other drawbacks as well.

With finite-element methods, the flow area is divided into a number of rigid elements. In modelling soil-water flow problems, triangular elements can be efficiently used to represent difficult geometries and to be more precise in regions where rapid changes are expected (e.g. near the soil surface or wetting fronts). Figure 11.19 shows an example of such a triangular nodal network. The corners of the triangular elements are designated as nodal points. In these nodes, state variables like matric head are specified. Via a number of techniques, one first gets a set of quasi-linear first-order differential equations, which are then discretisized and integrated in discrete time steps. The resulting set of non-linear equations is then solved, until iterations have converged to a prescribed degree of accuracy.

Finite-element methods are capable of solving complex flow geometries, with non-linear and time-dependent boundary conditions, while possessing great flexibility in following rapid soil-water movement. In many cases, the rate of convergence of the finite-element methods exceeds that of the finite-difference methods. A drawback of the finite-element method is the rather time-consuming and laborious preparation of the solution mesh. With an automatic mesh generation model, however, this problem can be considerably reduced. Another problem is that checking the finite-element solution by simple calculations is not always possible.

Initial Conditions

Initial conditions must be defined when transient soil-water flow is being modelled. Usually, values of matric head or soil-water content at each nodal point within the soil profile are required. When these data are not available, however, water contents at field capacity or those in equilibrium with the watertable might be regarded as the initial ones.

Upper Boundary Conditions

While the potential evaporation rate from a soil depends only on atmospheric

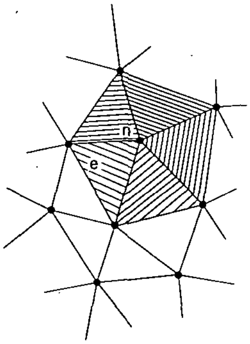

Figure 11.19 Network of triangular finite elements. The corners of the element e are designed as nodal points n, in which state variables are located

conditions, the actual flux through the soil surface is limited by the ability of the soil matrix to transport water. Similarly, if the potential rate of infiltration exceeds the infiltration capacity of the soil, part of the water is stored on the soil surface or runs off, because the actual flux through the top layer is limited by moisture conditions in the soil. Consequently, the exact upper boundary conditions at the soil surface cannot be estimated *a priori*, and solutions must be found by maximizing the absolute flux, as explained by Feddes et al. (1988).

Lower Boundary Conditions

The lower boundary of the unsaturated zone is usually taken at the phreatic surface, except if the watertable is very deep, when an arbitrary lower boundary is set.

Generally, one of the following lower boundary conditions are used:

- Dirichlet condition: The main advantage of specifying a matric head zero as the bottom boundary is that it is easy to record changes in the phreatic surface of a watertable. A drawback is that, with shallow watertables (< 2 m below soil surface), the simulated effects of changes in phreatic surface are extremely sensitive to variations in the soil's hydraulic conductivity;
- Neumann condition: A flux as lower boundary condition is usually applied in cases where one can identify a no-flow boundary (e.g. an impermeable layer) or where free drainage occurs. With free drainage, the flux is always directed downward and the gradient $dH/dz = 1$, so the Darcian Flux is equal to the hydraulic conductivity at the lower boundary;
- Cauchy condition: This type of boundary condition is used when unsaturated flow models are combined with models for regional groundwater flow or when the effects of surface-water management are to be simulated under conditions of surface or subsurface drainage (see Figure 11.20). Writing the lower boundary flux, q_b, as a function of the phreatic surface, which in this case is the dependent variable, one can incorporate relationships between the flux to/from the drainage system and the height of the phreatic surface. This flux-head relationship can be obtained from drainage formulae such as those of Hooghoudt or Ernst (see Chapter 8) or from regional groundwater flow models (e.g. Van Bakel 1986).

With the lower boundary conditions, the connection with the saturated zone can be established. In this way, the effects of activities that influence the regional groundwater system upon, say, crop transpiration can be simulated. The coupling between the two systems is possible by regarding the phreatic surface as an internal moving boundary with one-way or two-way relationships.

The most general form of the Cauchy condition can be written as

$$q_b = q_d + q_a \tag{11.55}$$

where

q_b = the flux through the lower boundary (m/d)
q_d = the flux from/to the drainage system (m/d)
q_a = the flux to/from deep aquifers (m/d) (Figure 11.20)

When the Cauchy condition is linked with a one-dimensional vertical- flow model,

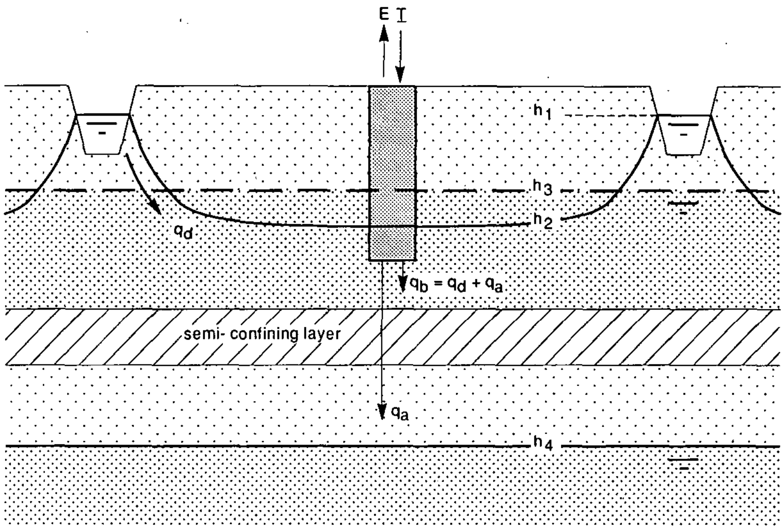

Figure 11.20 The flow situation (Cauchy lower boundary condition) for outflow from ditches and downward seepage to the deep aquifers: h_1 is the open water level; h_2 is the phreatic surface level; $h_3$is the level of the phreatic surface averaged over the area; and h_4 is the piezometric level of the deep aquifer

one can regard such a solution as quasi-two-dimensional, since both vertical and horizontal flow are calculated.

11.8.3 Model Data Input

Required Input Data

The simulation of water dynamics in the unsaturated zone requires input data on the model parameters, the geometry of the system, the boundary conditions, and, when transient flow is being simulated, initial conditions. The geometry parameters define the dimensions of the problem domain, while the physical parameters describe the physical properties of the system under consideration. Unsaturated-zone flow depends on the soil-water characteristic, $\theta(h)$, and the hydraulic conductivity, $K(\theta)$. If root water uptake is also modelled, parameters defining the relationship between water uptake by the roots and soil-water tension should be given, together with crop specifications. If a functional flux-head relationship is used as lower boundary condition, the parameters describing the interaction between surface water and groundwater and – if necessary – the vertical resistance of poorly permeable layers have to be supplied.

Before the models can be used to simulate the effects of different drainage strategies on the unsaturated zone, the models need to be calibrated. This can be done by comparing the results of model simulations with measured data from special calibration fields, and by adapting appropriate parameter values within the plausible range until simulation results and field measurements correspond to the desired degree. The calibrated model subsequently needs to be validated on another data set which was not used for the calibration. Only when calibration and val;idation are satisfactory can the model be applied to simulate the effects of drainage strategies for use in design procedures. A good calibration requires a profound analysis of the model parameters and of their influence on model results. (For details on model calibration, see specialized publications on this subject: e.g. Kabat et al. 1994).

Spatial Variability

One of the issues that complicate model calibration is spatial variability of soil hydraulic parameters and related terms of the water balance.

Most models of the unsaturated zone are one-dimensional. The hydrological and drainage problems that have to be modelled, however, concern areas, and have a spatial component, be it a local or a regional one. If the area were to be homogeneous in all its components, a point simulation could be representative of an entire region. The soil, however, is never homogeneous, but is subject to spatial variability. The variability of a parameter will not only influence the measuring program, but is also important for evaluating possible model accuracies.

The basic assumption of spatial variability in the unsaturated zone is that the porous medium is a macroscopic continuum with properties that are continuous functions of the space coordinates. The description of spatial variability by statistical techniques is referred to as 'geostatistical methods' (e.g. Jury et al. 1987).

Geostatistics can be used to determine the most efficient sampling schemes to obtain practical mean values of spatially dependent properties (e.g. soil hydraulic properties) within a specific soil or land unit. It can also be used to describe the variability of those properties and for the regionalization of point simulations. A proper application of the geostatistical approach may reveal field characteristics that are not apparent from conventional statistical analysis, but are not without significance for the properties being considered.

A frequently used technique to account for spatial variability is 'scaling'. Scaling can also be used to regionalize one-dimensional simulation models. In principle, scaling is a technique of expressing the statistical variability in, for instance, the hydraulic conductivity in functional relationships. By this simplification, the pattern of spatial variability is described by a set of scale factors, defined as the ratio between the characteristic phenomenon at the particular location and the corresponding phenomenon of a reference soil (Hopmans 1987).

Accuracy of Hydraulic Soil Parameters

The reliability of the results of simulation depends on the reliability of the model and on the accuracy of the parameters used in the model. The reliability and accuracy of the model are assessed by calibration and validation.

The required accuracy of input data should be relevant to the type of application and the type of problem to be solved (Wösten et al. 1987). It is also a function of the scale of the problem and of the sensitivity of the process to the parameters used. For site-specific studies, a higher accuracy is required than for regional studies. For processes directly dependent on the hydraulic soil properties (e.g. capillary rise, recharge to the groundwater, and solute transport), the required accuracy is higher than for processes that are related to the soil hydraulic properties in a more integrated way (e.g. seasonal crop transpiration or crop production).

Kabat and Hack-ten Broeke (1989) used the SWACROP simulation model to investigate the sensitivity of different land qualities to hydraulic soil parameters, using data collected for a maize crop over 1985 and 1986. Simulated pressure heads at 5 cm depth – a measure for the land qualities of workability and trafficability – were computed for three different K(θ) relationships (Figure 11.21). From the data for both years, they concluded that the three unsaturated conductivities led to considerable differences in trafficability, especially during wet periods (h > –100 cm). It appears that K(θ) needs to be known quite accurately for this direct land quality.

In contrast, the cumulative actual dry-matter-production curves, representing an integrated land quality, showed no (1985) or only minor (1986) differences as a result of the different K(θ)'s (Figure 11.21). This proves that the sensitivity to hydraulic soil parameters can decrease when more integrated land qualities are considered.

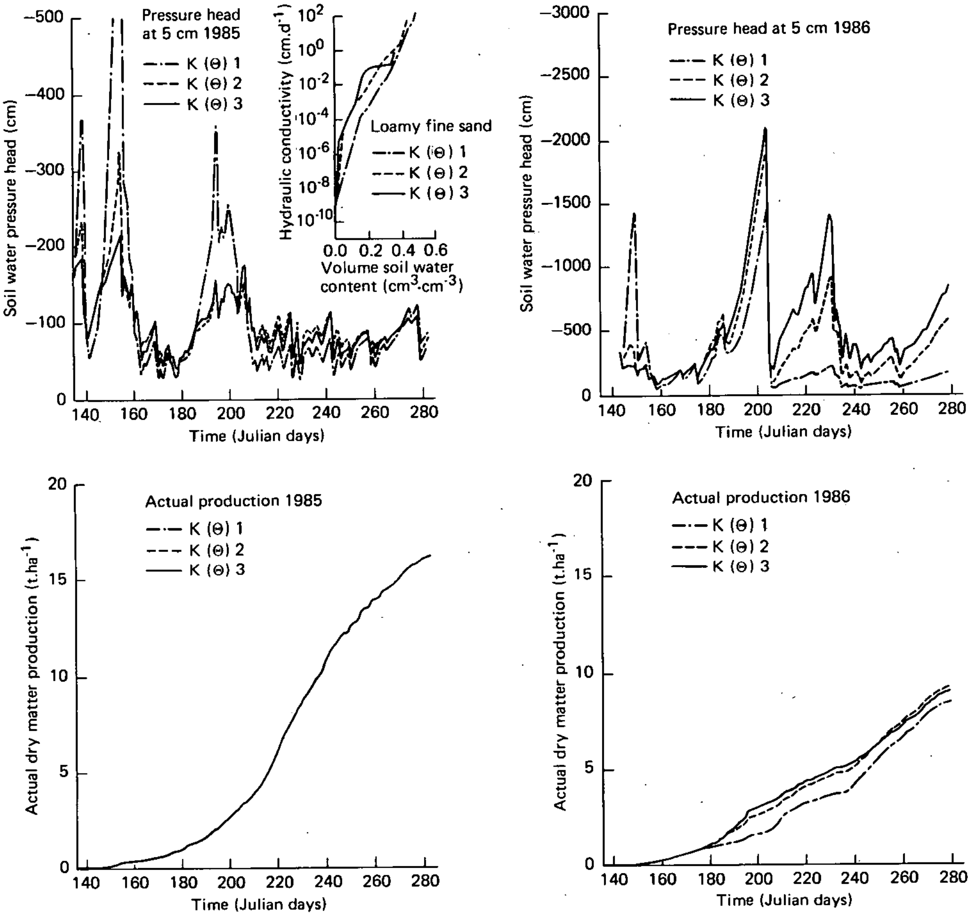

Figure 11.21 Sensitivity of the SWACROP model to the soil hydraulic parameter K(θ) in terms of pressure heads at 5 cm depth and actual dry-matter production (after Kabat and Hack-ten Broeke 1989)

11.8.4 Examples of Simulations for Drainage

Three examples of the application of the SWACROP simulation model in drainage problems will be given. Two of the examples concern water management under the moderate humid conditions of The Netherlands. The third concerns drainage and irrigation in the sub-tropical semi-arid conditions of Pakistan.

SWACROP (Kabat et al. 1992) describes transient water flow in a heterogeneous soil-root system, which can be under the influence of groundwater. It contains a crop-growth simulation routine, which describes the potential and actual crop production as a function of crop transpiration and of a few other environmental variables. Soil-water movement is simulated in response to pressure-head gradients according to Equation 11.49. Upper and lower boundary conditions can be set to reproduce a variety of common hydrological field situations. The model allows us to simulate subsurface and surface drainage systems, and irrigation.

Example 11.3 Drainage of Arable Land in The Netherlands

An integrated simulation approach, based on the agrohydrological model SWACROP, was developed by Feddes and Van Wijk (1990). In the integrated approach, land capability is quantified in terms of crop productivity under different conditions of climate, soil, drainage or irrigation, and farm management. The model can consider the following aspects, all of which can be affected by the operation of a drainage system via the soil-water conditions in the unsaturated zone:

- Number of days in spring when the soil-water content in the upper soil layer is low enough to permit soil cultivation and sowing or planting (farm-management aspect);
- Germination and crop emergence related to soil-water content and soil temperature;
- Water uptake, and growth and production of the crop between emergence and harvest;
- Number of workable days in autumn, when soil-moisture conditions allow harvesting operations (farm-management aspect).

The model calculated the effects of 15 combinations of drain depth and spacing on the yield of potatoes and spring cereals grown over 30 years on eight major soil types in The Netherlands. Three different definitions of seasonal yield were introduced: Y_{max}, the production under optimum water supply and earliest possible emergence; Y_{pot}, which includes retardation due to excessive wetness (insufficient drainage); and Y_{act}, representing for the actual water supply to account for the drainage effect on the yield:

$$\frac{Y_{act}}{Y_{max}} = \frac{Y_{pot}}{Y_{max}} \times \frac{Y_{act}}{Y_{pot}} \qquad (11.56)$$

The spring term, Y_{pot}/Y_{max}, accounts for a reduction in crop yield as a result of retarded planting and emergence. The growing season term, Y_{act}/Y_{pot}, quantifies the effects of too dry conditions (i.e. when the system is 'over-drained' and there are water shortages in the rootzone), or too wet conditions (when the system is 'under-drained') on the crop yield. The overall drainage effect, Y_{act}/Y_{max}, is the product of these two ratios.

We shall use the analysis of Feddes and Van Wijk (1990) and look at the yield of potatoes. For each of the eight major soil types in this study, the water-retention

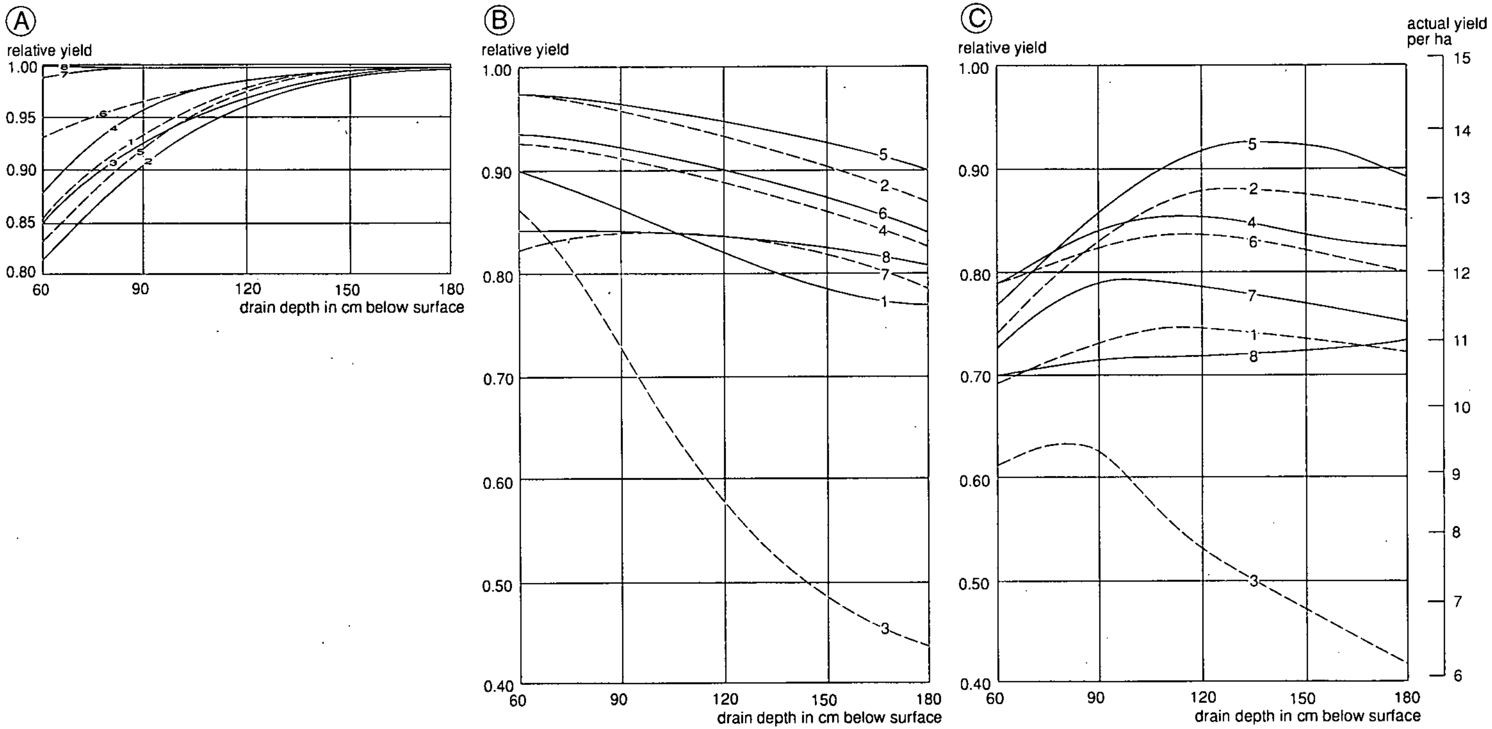

Figure 11.22 Drainage effects on potato yield based on a 30-year simulation for eight major soil types (Numbers 1-8) in relation to drain depth (after Feddes and Van Wijk 1990)

A. Decrease in relative yield due to too wet soil conditions and delayed workability and emergence in spring;

B. Decrease in relative yield due to moisture shortage during the growing season;

C. Reduction in total relative yield, the combined effect of too wet soil conditions in spring and water shortage during the growing season and hydraulic-conductivity characteristics were determined in the laboratory. The soils were: (1) a humus sand, (2) loamy sand, (3) peaty sand, (4) silty loam, (5) sandy loam, (6) loam, (7) silty clay loam, and (8) silty clay.

Figure 11.22A shows the effect of drain depth on the spring-reduced relative yield Y_{pot}/Y_{max}, averaged over the 30 simulated years. The most severe yield deficits occur at drain depths of 0.6 and 0.9 m in the sandy and loamy soils (Soils 1 to 5). The reductions are less pronounced for the loam soil (6), and almost absent for the clay soils (7-8). To avoid any risk of sub-optimum yields due to late planting on all soils, this simulation would lead to a recommended drain depth of 1.5 – 1.8 m.

Figure 11.22B shows the effect of drainage during the growing season on relative yield, Y_{act}/Y_{pot}. Yields are now decreasing with greater drain depths. This points to a general 'over-draining' for depths greater than 0.9 m. The greatest damage due to over-draining occurs on the peaty sand (3). Apart from the humus sand (1), which also seems somewhat susceptible to drought, the other soils show only a slight response to drain depth during the growing season.

Figure 11.22C shows the combined effect of drainage on the yield of the potatoes. We can draw the following conclusions:

- The optimum drainage depth depends strongly on the soil type. It varies from about 0.9 m for peaty sand (3) to about 1.3 – 1.4 m for sandy loam (5);
- The effect of soil wetness is most pronounced for the loamy sand (2) and sandy loam (5). Increasing the drain depth from 0.6 m to between 0.9 m and 1.2 m leads to a relative yield increase of the order of 10% for these soils. They have the highest unsaturated hydraulic conductivity under wet conditions and are characterized by an abrupt decrease in conductivity below a certain soil-water content upon drying. During wet conditions, they are thus subject to the largest capillary supply from the watertable (see Section 11.4.2);
- Heavier soils (6, 7, and 8) have a lower hydraulic conductivity and hence their response to increasing drainage depth is less pronounced;
- Except for the peaty sand (3), the effect of a too dry soil on overall drainage benefits is very small for drainage depths between 1.2 and 1.8 m.

The results of this study were used as the basis for a nationwide system to evaluate the effects of soil and drainage upon crop yields.

Example 11.4 Water Supply Plan in an Area with Surface Drainage

The economic feasibility of expanding the water supply for agriculture in a region in the north-eastern part of The Netherlands was investigated with the use of a special version of SWACROP (Werkgroep TUS-10-PLAN 1988; Van Bakel 1986). The region is intensively drained through a multiple-level canal system (Figure 11.23).

Figure 11.23 schematically shows that the water level in the main canals can be regulated via inlet and outlet structures. Water levels in the tertiary canals can be regulated in the same way. These tertiary canals drain the fields during the wet season. During the dry season, the inlet water infiltrates into the soil and creates better soil-water conditions in the rootzone (i.e. in the unsaturated zone) (see also Figure 11.20).

The region was divided into about 200 different combinations of soil type, hydrological properties, and land use. Each of these sets was modelled with the special version of SWACROP, which was extended with a module for manipulating the water

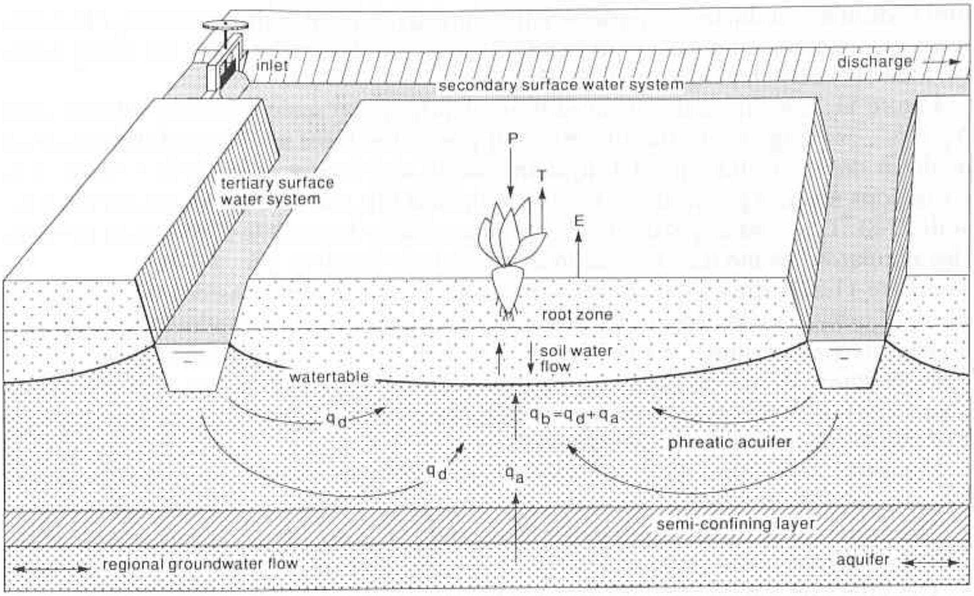

Figure 11.23 The modelled hydrological system in the water-supply plan in an area with intensive drainage (after Van Bakel 1986) (T). The lower boundary condition of the system was modelled as a Cauchy condition, the sum of the fluxes from the tertiary drainage system, q_d, and from the deep aquifer, q_a

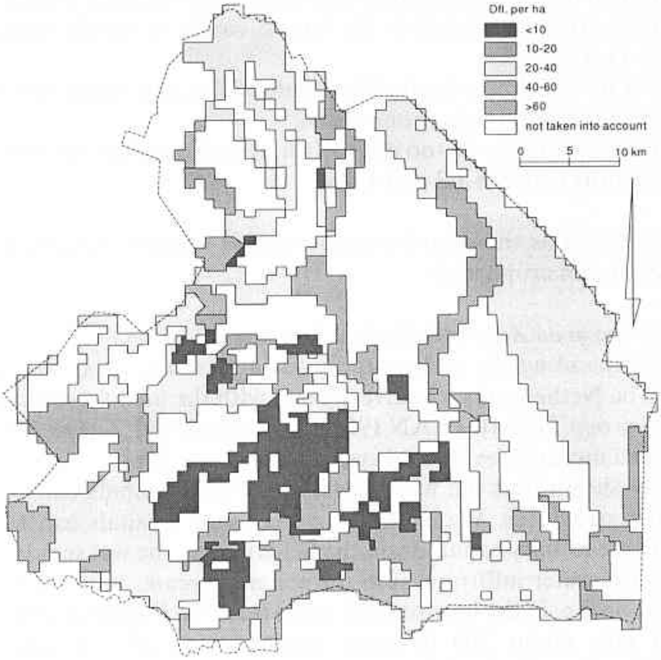

Figure 11.24 Simulated agricultural benefits of external water supply in the area with intensive drainage (after Werkgroep TUS-10-PLAN 1988); in Dutch guilders per hectare (1 DG = 0.5 US$)

level in (drainage) canals. The effects upon actual transpiration of the water supply through drainage canals (sub-irrigation), combined with supplementary sprinkler irrigation, were calculated for each set, using meteorological data for the years 1954-1983.

Since actual transpiration is related to soil-water conditions by a water-uptake function (as was explained in Section 11.6), the simulation of unsaturated-zone dynamics played a major role in this study. The simulation results (i.e. crop yield and other agricultural benefits) were expressed in monetary terms. On this basis, areas that would benefit from a water supply through the existing system of drainage canals could be located. Different degrees of such benefits could even be distinguished (Figure 11.24).

Example 11.5 Drainage to Combat Waterlogging and Salinity in Pakistan

Boers et al. (1993) used simulation model SWATRE (which is the soil-water component of SWACROP) to calculate the best drainage design for an irrigated area in the Indus Plains of Pakistan. The area is characterized by a subtropical semi-arid climate, with hot summers and cool winters, and monsoon rainfall, with high inter-annual variability. Major problems in the area are a high watertable that frequently hampers crop production, and secondary soil salinity.

The authors calibrated the model on a representative field in the area. The upper boundary conditions were potential crop evaporation, and rainfall and irrigation data. The lower boundary conditions were the watertable depth and the existing drainage design. The discharge to drains was calculated according to the Hooghoudt Equation (Chapter 8). The calibration was done by using different sets of independently measured hydraulic soil properties and by varying the correction factor for bare soil evaporation. The model was considered calibrated when weekly measured soil-water tensions at 0.15 m intervals over a depth of 0-2.0 m corresponded almost completely with the simulated ones for two consecutive years.

The calibrated model was subsequently used to calculate actual transpiration and (de)salinization for different drain depths and widths. The calculations were performed for a low-rainfall year, a moderate-rainfall year, and a high-rainfall year, selected from the climatic records of a nearby meteorological station. The objective of the model calculations was to maximize actual crop transpiration (as a measure of yield) and to mimimize the accumulation of salts in the rootzone.

The results indicated that the prevention of waterlogging during a wet monsoon was the most critical condition. Control of soil salinity appeared to be less critical.

Although these results are preliminary, the example shows that the simulation of water flow in unsaturated soils is capable of evaluating the influence of drainage design on vital conditions for crop production in areas prone to a combination of salinization and waterlogging.

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