eigen exemplaar

REPORT OF THE TNO AD-HOC GROUP

GROUNDWATER MODELS

AND

NUMERICAL COMPUTER SOFTWARE

TNO COMMISSION FOR HYDROLOGICAL RESEARCH

REPORT OF THE TNO AD-HOC GROUP

GROUNDWATER MODELS

AND

NUMERICAL COMPUTER SOFTWARE

TNO COMMISSION FOR HYDROLOGICAL RESEARCH

Report no. 2a.

The Hague, July 1978.

ADDRESS :

Bureau of the Committee for
Hydrological Research (CHO)

P.O. Box 297,

2501 BD THE HAGUE
The Netherlands.

CONTENTS Page

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

At the end of 1975 the Steering Committee of the TNO Commission for Hydrological Research took the decision in principle to proceed with the setting up of an ad hoc group on Groundwater Models and Computer Software.

The group was inaugurated on the 21st April 1976 by Prof. J.C. van Dam as Chairman of the TNO Commission for Hydrological Research and had the following composition:

S.I.E. Blok (Chairman)	Water Control and Public Works Dept. Data Processing Division (Dienst Informatieverwerking van de Rijkswaterstaat, Rijswijk);
A. Leijnse (Secretary)	National Institute for Water Supply (Rijks-instituut voor Drinkwatervoorziening, Voorburg);
J. Boonstra	International Institute for Land Reclamation and Improvement, Wageningen;
J. Bruyn	Drinking Water Company 'Oostelijk Gelderland' (N.V. Waterleidingmij Oostelijk Gelderland, Doetinchem);
T. Couwenhoven	Commission of Groundwater Law on Public Water Supply (Commissie Grondwaterwet Waterleidingbedrijven Utrecht);
R.A.Feddes	Institute for Land and Water Management (Instituut voor Cultuurtechniek en Waterhuishouding, Wageningen);
Th. J. van de Nes	Provincial Water Board, Gelderland (Provinciale Waterstaat van Gelderland, Arnhem).

The task of the group was as follows:

- To collect information on the requirements for, and the availability of, groundwater models and computer software in The Netherlands.
- In compliance with this task the ad hoc group has confined itself to collect only information of the existing numerical groundwater models for the quantity of water and the requirements for such models.

TNO = Organisation for Applied Scientific Research

The analog models, analytical solutions, and correlation and optimization techniques have not been considered. There has also been no attempt to give a detailed description of each model separately.

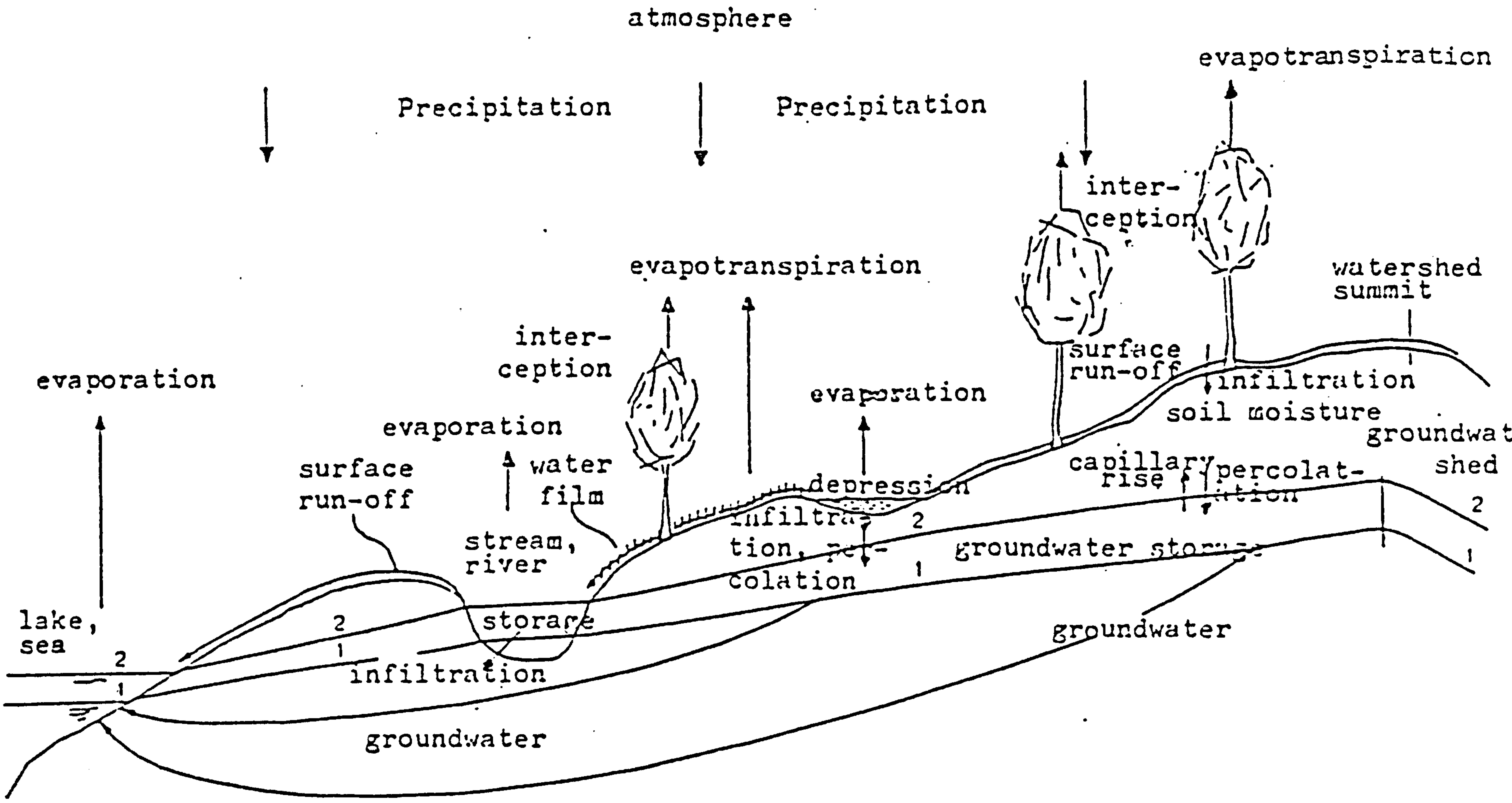
To carry out the task the group ran surveys among users and computer model engineers (see Appendices I, II, and III). These surveys were of an exploratory nature, no attempt being made at completeness.
The survey results are preceded in the report by short reviews of the theoretical back-ground to groundwater models (Chapter 2) and of a number of general aspects of computer software (Chapter 3). Here, too, no attempt has been made at completeness.
In Chapter 4 the results of the surveys are given (Tables 3-16 incl.), while in Chapter 5 the conclusions are presented.

2. FUNDAMENTALS

2.1 Description of the hydrological cycle

Figure 1 shows the natural hydrological cycle. The climatological data, which are decisive for precipitation and evaporation, are regarded as a natural given quantity.

Fig. 1 Natural hydrological cycle.



Part of the precipitation evaporates and the remainder is drained away, in which process the water passes through a number of storage reservoirs such as pools, surface water, soil moisture and groundwater.

Drainage ultimately takes place into seas, from which the water finds its way back into the atmosphere through evaporation.

Figure 2 is a diagrammatic representation of the most important natural hydrological processes in a flow basin. The arrows indicate the relations between the various storage reservoirs. Some of the precipitation does and some of it does not enter into the soil. The part which does not infiltrate is generally quickly drained off via the surface run-off system. In The Netherlands surface run-off is of relatively small significance. The precipitation which gets into the soil moisture system contributes on the one hand, to the actual evapotranspiration from agricultural crops and natural vegetation, and on the other hand to recharging the groundwater system. This latter quantity is termed effective precipitation.

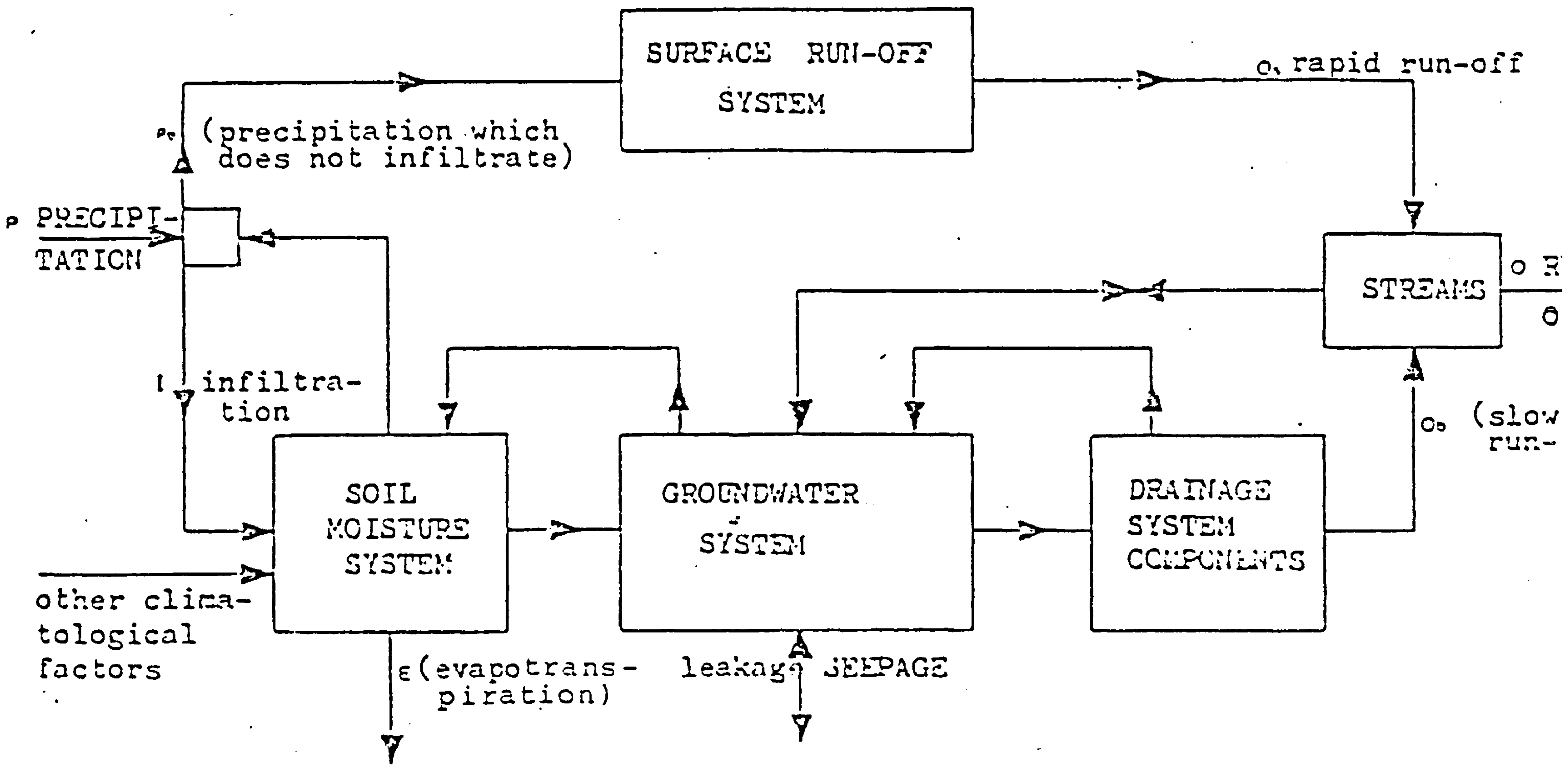


Fig. 2 Schematic hydrological model of a flow region.

Due to the relatively shallow groundwater level in The Netherlands, the groundwater system is strongly linked to the soil moisture and the drainage system. The groundwater level with respect to the land level determines both the possibility of capillary supply of water to the soil moisture system (from which the vegetation draws its water) and the possibility of storage of excess precipitation. The relationship between the systems makes it necessary that human intervention in the groundwater system, as for example groundwater extraction, openwater level control, etc., should be studied in relation to the soil moisture system and the surface water system. As an illustration of this relationship, Table 1 gives a worked example taken from the interim report of the Commission for Studying Water Management in Gelderland (1976).

The worked example on groundwater extraction in Table 1 gives the water balance in mm for an area around a pumping station in East Gelderland for various water removal strategies during the growth season of 1971. The effect of the extraction on the various terms in the water balance sheet is clearly illustrated. Such balance sheets can, for example, be drawn up for changes in the level control.

Table 1: Worked example of groundwater extraction

The water balance sheet for
I : the situation without extractio
II : the situation with extraction
III : the situation with "winter extraction"
IV : the situation with double extraction and the consequences for the terms in the water balance sheet, situations II, III and IV always being compared with I.

- -

Water Balance (mm)		I	II	III	IV
In:	Precipitation	508	508	508	508
	Change in storage	55	65	66	71
		563	573	574	579
Out:	Evapotranspiration	465	460	461	456
	Surface water drainage	23	21	19	16
	Groundwater drainage	75	46	48	14
	Removed	0	46	46	93
		563	573	574	579

Consequences for :
- the terms in the water balance (mm)

afname	Decrease in evapotranspiration	5	4	9
	Decrease in surface water drainage	2	4	7
	Decrease in groundwater drainage	29	27	61
toename	Increase in storage	10	11	16
	Total removal	46	46	93

2.2 Physical and mathematical theory

In what follows the theory of groundwater flow will be briefly dealt with. To this end, the concept of groundwater potential is first explained, the basic equations are then derived and finally the boundary conditions are discussed.

2.2.1 Groundwater potential

Water flows from points of high energy to points of low energy. The energy state of water in the soil can be described by the concept of potential. This is an expression of the capacity of a unit mass of water to perform work in comparison with a unit mass of free water which by definition has a potential equal to zero. In hydrology, preference is given to considering the potential not per unit of mass, but per unit of weight. In this case energy has the dimensions of length, which is usually expressed in "length of water column". In addition it is assumed that the density of water ρ(kg.m^{-3}) and the acceleration due to gravity g (m.s^{-2}) are constant. The potential is defined in terms of the reference state of water (with a chemical composition which is the same as that of water in the ground) at atmospheric pressure and a zero reference plane.

The potential consists in theory of a number of partial potentials:

$$\phi = \psi_g + \psi_m + \psi_{p.hydr} + \psi_{p.ext} + \psi_{osm} \quad (m) \qquad (1)$$

where

ϕ = total water potential
ψ_g = gravitational potential, due to gravity
ψ_m = matrix potential, due to the interaction of soil and water
$\psi_{p.hydr}$ = hydrostatic potential, due to the hydrostatic pressure
$\psi_{p.ext}$ = pneumatic potential, due to the external gas pressure
ψ_{osm} = osmotic potential, due to the osmotic forces.

The gravitational potential ψ_g is at every point equal to the height of above an arbitrary reference plane.

The matrix potential ψ_m is zero in the saturated zone and negative in the unsaturated zone.

ψ_m is often written simply as ψ and termed the matric pressure head ("capillary potential"). To avoid the difficulties of a negative pressure head in the unsaturated zone, a moisture tension or suction ψ^* (= $-\psi$) is often spoken of.

The hydrostatic potential $\psi_{p.hydr}$ is zero in the unsaturated zone and equal to $p_h/\rho g$ in the saturated zone, where p_h is the hydrostatic pressure of the water. It is equal to the length ℓ of the liquid column in a piezometer.

We can neglect the pneumatic potential $\psi_{p.ext}$ because the external pressure in the ground is practically equal to the atmospheric pressure.

The osmotic potential ψ_{osm} is equal to zero because we are measuring with respect to free water with the same chemical composition.

All this taken together means in practice that in a system with z as the vertical ordinate, with the upward direction positive :

$\phi = z + \ell$ for the saturated zone (m)

$\phi = z + \psi$ for the unsaturated zone (m).

Differences in ϕ determine the direction and magnitude of the groundwater flow.

2.2.2 General basic equations

The basis for calculating groundwater flow is Darcy's law. In its general, 3-dimensional form this is as follows

$$\bar{q} = - k\ (S_w)\ \nabla \phi \qquad (2)$$

where

$\bar{q} = (q_x, q_y, q_z) =$ flux $(m^3.m^{-2}.d^{-1})$

$k =$ permeability coefficient $(m.d^{-1})$

$S_w =$ relative water saturation $(0 \leqslant S \leqslant 1)$ $(m^3.m^{-3})$

= groundwater potential (m)

$\nabla\phi = (\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}, \frac{\partial\phi}{\partial z}) = \mathrm{grad}\ \phi$ $(m.m^{-1})$.

In general, the permeability coefficient k is not only dependent on S_w, but also on the location (inhomogeneity) and the direction of flow (anisotropy) and temperature.

The continuity equation is found by setting up the mass balance for an infinitesimally small volume element:

$$-\nabla \left[\rho\ \bar{q}\right] + \rho Q = \frac{\partial}{\partial t}\left[\rho n S_w\right] \qquad (3)$$

where

$$\nabla \left[\rho \bar{q}\right] = \frac{\partial}{\partial x}\left[\rho q_x\right] + \frac{\partial}{\partial y}\left[\rho q_y\right] + \frac{\partial}{\partial z}\left[\rho q_z\right] = \mathrm{div}\left[\rho \bar{q}\right] \qquad (3a)$$

$\rho =$ density of the water $(kg.m^{-3})$

$Q =$ quantity of water introduced from outside the system per unit volume, per unit time $(m^3.m^{-3}.d^{-1})$

$n =$ porosity (pore volume) $(m^3.m^{-3})$

$t =$ time (d)

Substitution of Darcy's law in the continuity equation gives the general differential equation for groundwater flow:

$$\nabla \left[\rho k(s_w) \nabla \phi \right] + \rho Q = \frac{\partial}{\partial t} \left[\rho n s_w \right] \qquad (4)$$

Because the same flow equation can be used as the starting point for both the saturated and the unsaturated zone, it is obvious that an integral numerical approach to both systems should be sought. This has been worked on abroad at a 2-dimensional level by, among others, Rubin (1968), Hornberger et al (1969), Taylor and Luthin (1969), Verma and Brutsaert (1970) and Neuman (1973). However, the difficulty arising in this connection is that the hydraulic permeability in the unsaturated zone, in contrast to that in the saturated zone, is not constant, but depends on the relative water saturation of the soil. As a result of this a numerical approach to the flow equation is particularly troublesome. Consequently an integral solution of the whole flow for the saturated zone, in spite of efficient numerical computer techniques, will in general lead to to models which require considerable computer time. Freeze (1971) also found for a 3-dimensional system that an enormous computer memory capacity was required if calculations were done for rather large areas. In addition, in all cases the evaporation was taken as given, and thus independent of the flow in the unsaturated zone. In The Netherlands Feddes (1974) has given a solution for 2-dimensional unsaturated/saturated flow in a vertical plane, in which the evaporation via water up-take by roots is also taken into consideration.

For the above reasons a clear distinction has to be made between models for saturated groundwater flow (1,2 and 3-dimensional) and models for unsaturated groundwater flow (mainly 1-dimensional vertical). A link between the two systems is possible to some extent via the term Q in equation (4), which applies to both the saturated and the unsaturated system. In The Netherlands this approach has been chosen for a 3-dimensional system (by de Laat et al 1975, 1976) to achieve an economically usable model for large areas. In this case, the change in groundwater level is calculated with the saturated model; the flux through the phreatic surface resulting from this is then used as the boundary condition at the bottom of the unsaturated model.

Before embarking on a further development of equation (4) for both saturated and unsaturated groundwater flow, an elucidation of the term Q appears desirable. From the following it will appear that this term depends on one hand on the boundaries of the system under consideration and the model assumptions, while on the other hand it indicates the relation to groundwater control (removal, infiltration, level control, surface water and drainage).

From the definition of Q, it appears that it is determined by the boundary of the groundwater system. For the entire system (saturated + unsaturated) Q, as a function of x, y, z and t, can be broken down as:

$$Q = Q_e + Q_o + Q_g + Q_w \qquad (5)$$

where

Q_e is the artificial supply or removal of groundwater,

Q_o is the drainage to or supply from the surfacewater,

Q_g is the vertical flow between the water-bearing formations and

Q_w is composed of the supply to, and the drying out of, the unsaturated zone.

If only the saturated groundwater system is considered, Q_w in (5) is defined as the flow to or from the unsaturated zone. In most models Q_w is in that case set equal to the effective precipitation, which is equal to the precipitation minus evapotranspiration. The relation between groundwater and surface water Q_o is determined by the potential difference between the groundwater and the surface water and the resistances which must be overcome, such as the horizontal, radial and entrance resistance. In the case that several water-bearing formations are separated by layers of poor permeability, this system is usually approximated by horizontal groundwater flow in the various water-bearing formations. Equation (4) is then worked out for every water-bearing formation. The link between the equations takes place through the term Q_g in equation (5). This term represents the vertical flow between the water-bearing units. This is determined by the potential difference between the water-bearing formations and the vertical resistance which has to be overcome as a result of the layer of poor permeability.

In considering an exclusively 1-dimensional unsaturated groundwater system, Q consists exclusively of Q_w, which is determined by the vegetation and the meteorological system. This will come up again in the basic equations for the unsaturated zone. The link with the saturated system will then also be given some attention.

2.2.3 Basic equations for the saturated zone

In the case of saturated groundwater flow $S_w = 1$, and the permeability coefficient k is constant.

Equation (4) can then be written as :

$$\nabla \left[\rho k \nabla \phi \right] + \rho Q = \frac{\partial}{\partial t} \left[\rho n \right] \qquad (6)$$

Here both n and ρ are functions of the potential ϕ. The product can be written as:

$$\frac{\partial}{\partial x}(k\frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(k\frac{\partial \phi}{\partial y}) + \frac{\partial}{\partial z}(k\frac{\partial \phi}{\partial z}) + Q = S\frac{\partial \phi}{\partial t} \qquad (7)$$

where

ϕ_o = a reference value for ϕ (m)

C = the compressibility of the water-filled soil (m^{-1})

To an approximation : $\rho \approx \rho\ (\phi_o)$ = constant.

If C is assumed constant, then

$$\frac{\partial}{\partial t} \left[\rho n \right] = \rho n(\phi_o)\ C \frac{\partial \phi}{\partial t} \qquad (8)$$

Substitution of (8) in (6) then gives :

$$\nabla \left[k \nabla \phi \right] + Q = S \frac{\partial \phi}{\partial t} \qquad (9)$$

or

$$\rho n = \rho(\phi_o) . n\ (\phi_o) . \left[1 + C(\phi - \phi_o) \right] \qquad (9a)$$

where

S = n (ϕ_o) C = the storage coefficient, which is the quantity of water released per unit volume of ϕ is decreased by one unit ($m^3.m^{-3}.m^{-1}$).

In most cases it will not be necessary to describe the groundwater flow in 3-dimensions.

In the case of purely horizontal flow, for example, the groundwater potentioal ϕ is not dependent on the vertical co-ordinate z. The differential equation for 2-dimensional flow can then be derived in an identical manner

$$\frac{\partial}{\partial x} (kD \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y} (kD \frac{\partial \phi}{\partial y}) + Q = S \frac{\partial \phi}{\partial t} \qquad (10)$$

where

D = the thickness of the water-bearing formation (m).

In this case the definitions of Q and S are :

Q = the quantity of water supplied from outside the system <u>per unit area,</u> per unit time ($m^3.m^{-2}.d^{-1}$).

S = the quantity of water released <u>per unit surface area</u> if ϕ is decreased by 1 unit ($m^3.m^{-2}.d^{-1}$).

If this flow only takes place in one direction, the equation is

$$\frac{\partial}{\partial x}\left(kA\frac{\partial \phi}{\partial x}\right) + Q = S\frac{\partial \phi}{\partial t} \qquad (11)$$

where

A = area of cross-section perpendicular to the x-direction (m^2)

In this case, too, the definition of Q and S is different, namely:

Q = quality of water supplied from outside the system <u>per unit length</u>, per unit time. ($m^3 . m^{-1} . d^{-1}$).

S = the quantity of water released <u>per unit length</u>, if the groundwater potential is decreased by one unit ($m^3 \cdot m^{-1} . m^{-1}$).

In the case of steady flow, i.e. if $\frac{\partial \phi}{\partial t} = 0$, equations (9a), (10) and (11) become the well known Laplace equation for three-, two- and one-dimensional flow respectively.

Depending on the boundary conditions, an analytical solution of these equations can, generally speaking, only be found for very simple cases. For more complex cases, an appropriate solution can be found using numerical methods.

2.2.4 Basic equations for the unsaturated zone

In the discussion of the concept of potential it was pointed out that the matric pressure head of the soil moisture is due to the local interaction of soil and water. At, and beneath, the phreatic surface $\psi = 0$. In the equilibrium state ψ decreases with increasing height above this surface, the soil can retain the water with increasing difficulty and an increasing number of pores will lose water. As a result of this the moisture content θ of the soil will decrease. This results in a certain relationship between θ and ψ :

$$\theta = f(\psi) \qquad (12)$$

Such a relationship is called the water retention curve or the moisture characteristic of the soil. As remarked earlier, in practice tensions (ψ^*, where $\psi^* = -\psi$) are preferred to negative pressures. The value of ψ^* varies in practice from 0 to 10^7 cm. To be able to express this range graphically without difficulty, the concept of pF is introduced, which is defined as the logarithm of the suction/tension in cm water column.

$$pF = {}^{10}\log(\psi^*) \qquad (13)$$

The moisture characteristics are usually determined by removing water from an initially wet sample of soil. If water is added to an initially dry sample, the relationship $\theta(\psi)$ is often different, then hysteresis occurs. In general, this hysteresis is not taken into consideration.

For saturated flow the total pore volume of the soil is available for flow; in the unsaturated zone, however, some of the pores, being filled with air, do not participate in the flow. The permeability coefficient k is therefore not constant, but depends on the relative water saturation S_w. By definition, the relative water saturation is equal to the quotient of the volumetric moisture content θ and the pore volume n ($S_w = \theta/n$).

For a given type of soil the permeability coefficient k is thus dependent on the moisture content θ or (since $\theta = f(\psi)$) on the local pressure head ψ:

$$k = f(S_w) \text{ or } k = f(\theta) \text{ or } k = f(\psi) \qquad (14)$$

In the case of unsaturated flow for the hydraulic permeability coefficient k, the term capillary conductivity is sometimes used.

For practical applications ϕ and S_w in equation (4) are expressed in terms of the height of the location z, the pressure head ψ and the volumetric moisture content θ. If one substitutes $\phi = z + \psi$ and $nS_w = \theta$, then equation (4) becomes

$$\nabla [k(\theta) \nabla (z + \psi)] - Q = \frac{\partial \theta}{\partial t} \qquad (15)$$

where

Q = sink term which represents the water uptake by the roots (m^3 water. m^{-3} soil. d^{-1}) *

ρ is assumed to be constant.

In view of the fact that the flow in the unsaturated zone takes place mainly in the vertical direction (capillary rise or infiltration), we can confine ourselves in practice to 1 dimension:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[k(\theta) \frac{\partial \psi}{\partial z} \right] + \frac{\partial k(\theta)}{\partial z} - Q \qquad (16)$$

In these 1-dimensional vertical models, precipitation is introduced as a boundary condition.

In equation (16) the two dependent variables θ and ψ are involved. Use is therefore often made of the relationship:

$$D = k \frac{d\psi}{d\theta} \qquad (m^2 . d^{-1}) \qquad (17)$$

* The term Q is often the most important reason for water removal from the unsaturated zone, but this must be left out of consideration here.

which transforms (16) to

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[\mathbb{D}(\theta)\frac{\partial\theta}{\partial z}\right] + \frac{\partial k(\theta)}{\partial z} - Q \qquad (18)$$

The factor D is termed the "diffusivity" coefficient, because the transformation used makes the flow analagous to a diffusion process.
Equation (18) is well known as the θ - form of the general flow equation, which is only applicable to uniform soil profiles.

The so called differential moisture capacity Γ

$$\Gamma = \frac{d\theta}{d\psi} \qquad (m^{-1}) \qquad (19)$$

may be introduced in equation (16), so that (16) becomes

$$\Gamma(\psi)\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left[k(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right)\right] - Q \qquad (20)$$

In practice, the relationships $\theta(\psi)$, $k(\theta)$, or $k(\psi)$ and $\mathbb{D}(\theta)$ are often approximated by empirical formulae. In that case analytical solutions can be found for equations (18) and (20) for simple flow problems. In most of the cases, however, one has to resort to numerical methods of solution.

Boundary conditions

In order to be able to solve the differential equations which describe the groundwater flow, they must be provided with initial and other boundary conditions. As an initial condition a known value of the potential at time t = 0 is often taken:

$$\phi(\chi, 0) \quad \phi_0(\chi), \qquad (21)$$

where $\chi = (x, y, z)$ are the spatial co-ordinates.

As regards the conditions which must be known at every point along the boundary R of the groundwater system, three types of boundary conditions can be distinguished:

- Dirichlet type: the value of the potential is given:

$$\phi(\chi, t) = \phi_p(\chi, t) \text{ at } R \qquad (22)$$

- Neumann type: the value of the flux perpendicular to the boundary is given:

$$[k\,\nabla\phi]\, n_i = -V_p(\chi, t) \text{ at } R \qquad (23)$$

- mixed type: the value of the potential is given at section R_1 of the boundary and the value of the flux at complementary section R_2 of the boundary.

This latter-type means a combination of (22) and (23).

In the above equations ϕ_p and V_p are defined functions of X and t, and n_i is the unit vector perpendicular to the boundary R. The boundary conditions are valid both for the saturated and the unsaturated zone.

In the last case both the suction and the moisture content can be used. In practice, these boundary conditions are often not known, and consequently other conditions must be set. These can be derived from the meteorological conditions at the soil surface.

Along the boundary plane between soil and air, the soil may lose water to the atmosphere as a result of evaporation or it may gain water as a result of infiltration. While the potential (i.e. the maximum possible) rate of evaporation of a given soil depends only on the meteorological conditions the actual evaporation flux through the soil surface is determined by the possibility of the porous medium letting water through from below. In the same way one can say that if the potential infiltration flux (e.g. the precipitation intensity) exceeds the infiltration capacity of the soil, part of the water goes to surface run-off. In this case, too, the potential infiltration rate is determined by the external atmospheric (or other) conditions, while the actual flux depends on the prevailing moisture situation in the soil. The exact boundary conditions can therefore not be predicted *a priori*. A solution can be sought in maximizing the absolute value of the flux (using the correct sign) which is subject to the conditions

$$\left[k(\psi) \left(\frac{\partial\psi}{\partial z} + 1 \right) \right] \leqslant \left[E^{*}_{s} \right] \tag{24}$$

$$\psi_1 \leqslant \psi \leqslant 0 \tag{25}$$

where E^{*}_{s} is equal to the potential soil evaporation flux and ψ_1 is the maximum allowed pressure head at the soil surface, corresponding to conditions which can be termed 'air dry'. Both quantities can be determined on the basis of meteorological data. For an application of this type of atmosphere boundary conditions, see, for example *Feddes et al,* (1974).

2.3 *Methods of solution*

From the survey of the existing groundwater models it turns out that the great majority of models are based on the finite difference method or on the finite element method. Both methods will be dealt with briefly.

In a number of models use is made of Runga-Kutta integration (e.g. *Van den Akker,* 1975). In addition, in recent years a number of new developments have been announced, which may well lead to attractive applications:

- analytical function method (*van der Veer*, 1976)
- vortex theory (*de Josselin de Jong,* 1977)
- source covering (*Berkhoff*).

2.3.1 Finite difference method

Introduction

In the finite difference method, a grid is superimposed on the region of interest in the plane of space and time. The method is based on the principle of replacing the derivatives at every mesh point of this grid by ratios of the changes in the variables over a small but finite interval:

$$\frac{\partial\phi}{\partial x} = \lim_{x\to 0}\frac{\Delta\phi}{\Delta x} \simeq \frac{\Delta\phi}{\Delta x} \qquad (26)$$

In this way a continuous boundary-value problem is reduced to a set of algebraic equations (Forsythe et al, 1960; Smith, 1965; Remson et al, 1975). In the mathematical formulation use is made of the one-dimensional form of the equation for groundwater flow (11). The mathematical formulation for the two- and three-dimensional form can be derived in the same way. It is convenient to make equation (11) dimensionless by reducing it to:

$$\frac{\partial^2\phi}{\partial x^2} + q = \frac{\partial\phi}{\partial t} \qquad (27)$$

Mathematical formulation

An explicit approximation is obtained by replacing the space derivative (27) by a difference approximation at time step j, while the time derivative is replaced by the difference approximation between time steps j and j + 1. In this case equation (27) becomes:

$$\frac{\phi_{i+1,j} - 2\phi_{i,j} + \phi_{i-1,j}}{(\Delta x)^2} + \frac{\phi_{i,j+1} - \phi_{i,j}}{\Delta t} \qquad (28)$$

Applied to every mesh-point this approximation contains one unknown at time step j + 1 which can be explicitly solved from the three known values at time step j (see figure 3).

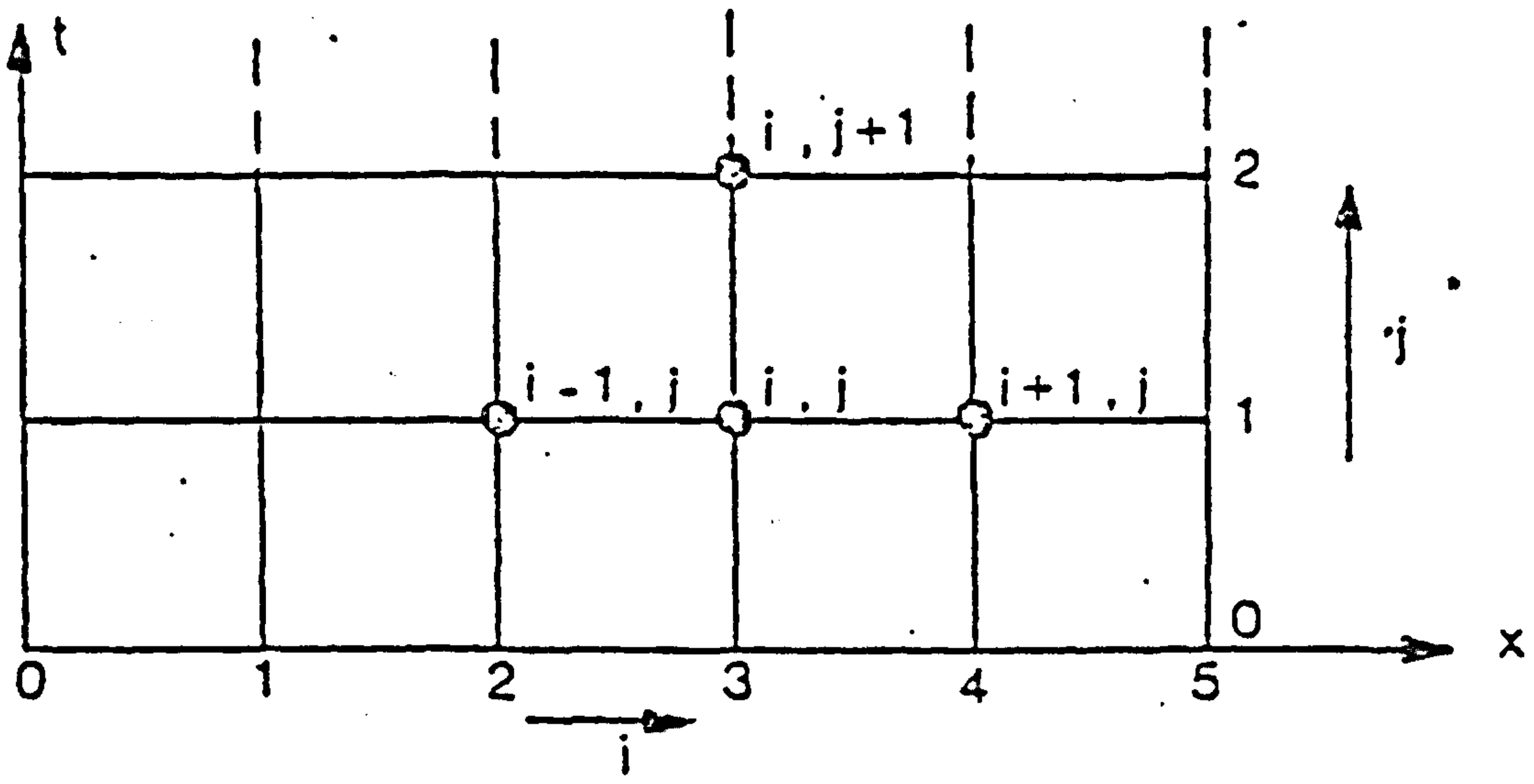


Fig. 3 Square grid superimposed on the x, t plane for explicit approximation.

It is possible to calculate the value of the function ϕ at all the mesh-points time step by time step, if the function ϕ is prescribed at the boundaries. In this way the solution "marches" forward in time. It can be shown that the explicit approximation can only be applied if Δt is not greater than $\frac{1}{2} (\Delta x)^2$. (Forsythe et al, 1960; Smith, 1965).

An implicit approximation is obtained by replacing the space derivative by the difference approximation at time step j + 1.
Equation (27) then becomes:

$$\frac{\phi_{i+1,\, j+1} - 2\phi_{i,j+1} + \phi_{i-1,j+1}}{(\Delta x)^2} + q = \frac{\phi_{i,j+1} - \phi_{i,j}}{\Delta t} \qquad (29)$$

From equation (29) $\phi_{i,j+1}$ cannot now be explicitly solved because the other terms still contain unknowns.

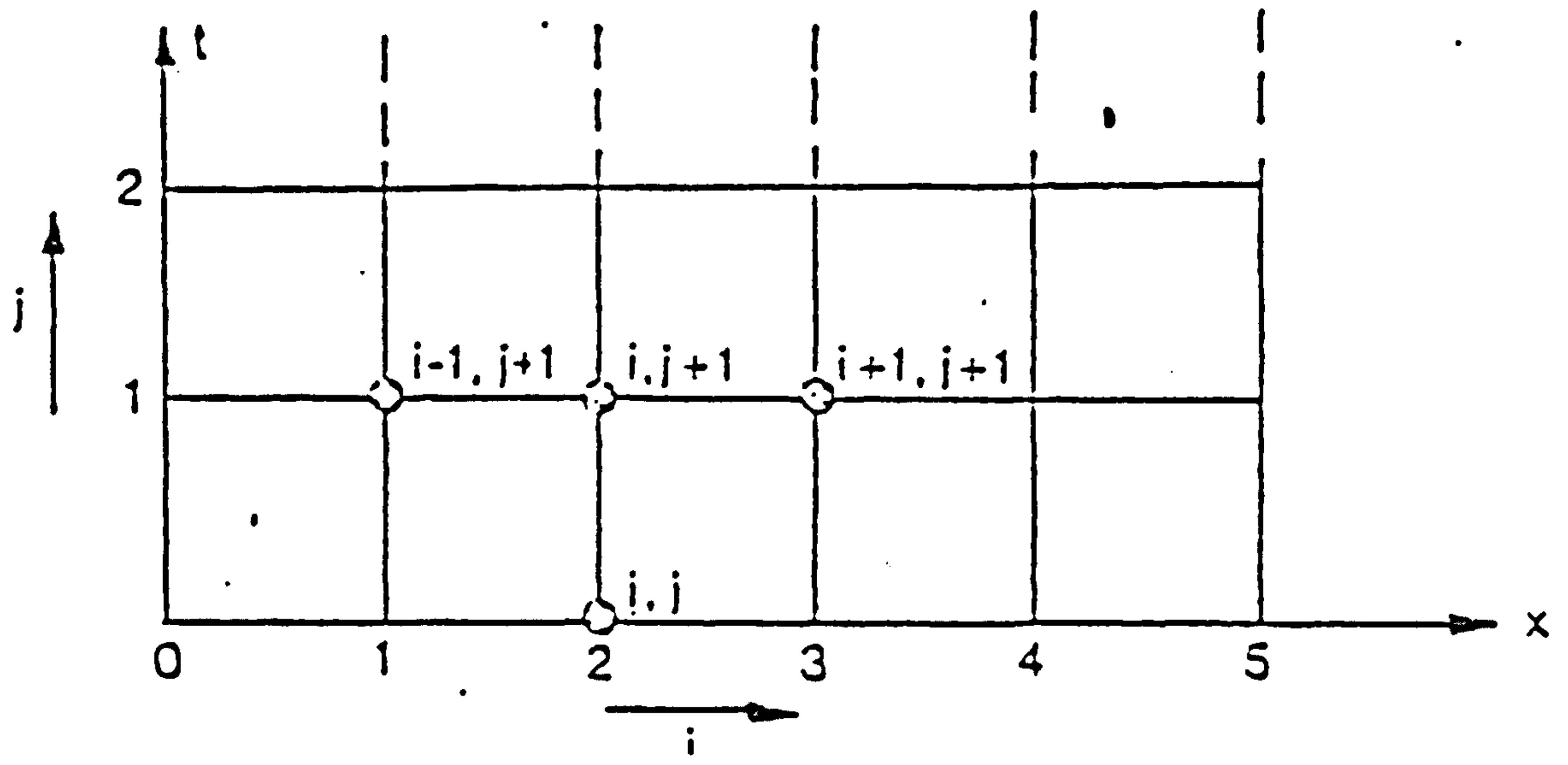


Fig. 4 Square grid superimposed on the x, t plane for implicit approximation

At the time step j + 1 (see figure 4) equation (29) can be set up for i = 1, 2, 3, 4; then there are four equations containing four unknowns which can be solved simultaneously. This procedure is repeated for each time step. The advantage of the implicit approximation is that Δt and Δx can be chosen independently of each other.

In the literature a number of other difference-approximation methods have been described. The following methods should be mentioned.

- the Crank-Nicolson approximation which proceeds from the central difference approximation (Crank et al, 1974);
- the Douglas-Jones approximation which is a modification of the Crank-Nicolson method (Douglas et al, 1963);

- the Peaceman-Rachford approximation, which uses the explicit and implicit approximation alternately (Peaceman et al, 1955).

Boundary conditions

The description given of the explicit and implicit approximation proceeded from boundary conditions of the Dirichlet type. However, for groundwater flow problems boundary conditions of the Neumann type or of the mixed type often apply. This adds an unknown to the problem, viz. the value of the function itself at the boundary. Suppose that for equation (27) the following boundary condition is given:

$$k \frac{\partial \phi}{\partial x} = c \quad \text{for } x = 0,\ t > 0 \qquad (30)$$

For every time step an additional mesh-point (- 1, j+1) is now added to the grid. This means that for each time step there are two additional unknowns, viz. $\phi_{-1,\ j+1}$ and $\phi_{0,\ j+1}$. For this reason, equations must be derived for these unknowns. The first follows from equation (30):

$$\frac{\phi_{1,j+1} - \phi_{-1,j+1}}{2\ \Delta x} = \frac{c}{k} \qquad (31)$$

As the second equation one can, for example, set up an implicit difference approximation (see equation (29)) for mesh-point 0, j+ 1:

$$\frac{\phi_{1,j+1} - 2\phi_{0,j+1} + \phi_{-1,j+1}}{(\Delta x)^2} = \frac{\phi_{0,j+1} - \phi_{0,j}}{\Delta t} \qquad (32)$$

In the same way as in the explicit and implicit approximation the problem can now be solved time step by time step. In the literature other approximations have also been described to derive boundary conditions of the Neumann type (Lothin, 1958)

2.3.2 Finite element method

Introduction

In the finite element method, just as in the case of the finite difference method, time and space are discretised. The area under consideration is divided into a number of segments called elements. In principle these elements can have an arbitrary shape and size. The choice of the shape and size of the element is determined by the geometry of the area under investigation and the accuracy required. In those areas where large differences in groundwater potential occur (for example, around pumped wells) the use of many small elements will be necessary to achieve the accuracy required.

The vertices of the elements are the mesh-points. If there are N mesh-points, an approximate solution ϕ_b for ϕ is defined as a linear combination of N basic functions Li:

$$\phi_b(x,y,z,t) = \sum_{i=1}^{N} \phi_i(t) \quad L_i(x,y,z) \qquad (33)$$

Moreover, the functions L_i are chosen such that:

$L_i = 1$ at the mesh-point $j = 1$

$L_i = 0$ at the mesh-point $j \neq 1$

The coefficients ϕ_i are therefore the values of the approximate solution ϕ_b at the mesh-points i.

These coefficients are determined in such a way that the approximate solution ϕ_b is as close as possible to the actual solution for ϕ.

Mathematical formulation

The mathematical formulation proceeds from the 2-dimensional form of the equation for groundwater flow (10) The formulation for 3 dimensions or 1 dimension is completely analogous.

In order to determine the coefficients ϕ_i from equation (33) in a manner such that the approximate solution is as close as possible to the actual solution for ϕ of equation (10), two methods are generally used, viz. a variational method and a residual method. Both methods have been extensively described in the literature (Zienkiewicz, 1971; Finlayson, 1972; Norrie et al, 1973). In principle these methods proceed as follows:

- variational method (particularly the Rayleigh-Ritz method):

  A function F $(\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}, \phi, x, y)$ can be found such that the integral of F over the area G under consideration

  $$I = \iint_G F \, d\, G \qquad (34)$$

  is a minimum for the solution for ϕ of equation (10). For equation (10) this function is as follows:

  $$F = \tfrac{1}{2} \{ \; kD \, (\frac{\partial\phi}{\partial x})^2 + kD \, (\frac{\partial\phi}{\partial y})^2 \} - \phi \{ Q - S \frac{\partial\phi}{\partial t} \} \qquad (35)$$

  If the approximate solution ϕ_b is substituted in F, then the integral I can be calculated by carrying out the integration element by element.

I is then minimized using the coefficient ϕ_i by putting:

$$\frac{\partial I}{\partial \phi_i} = 0 \quad i = 1,N \qquad (36)$$

If the derivative with respect to time is discretised as follows:

$$\frac{\partial \phi}{\partial t} \quad \frac{\phi - \phi^o}{\Delta t} \qquad (37)$$

where ϕ is the value to be calculated and ϕ^o the known value of ϕ at the beginning of the time step Δt, then equations (36) are a system of N linear equations in the N unknown ϕ's; The solution of these can be found using the well-known methods;

- residual method (particularly Galerkin's method):

  Substitution of the approximate solution ϕ_b (33) in equation (10) gives:

  $$R = \frac{\partial}{\partial x} \{kD \frac{\partial \phi_b}{\partial x}\} + \frac{\partial}{\partial y} \{kD \frac{\partial \phi_b}{\partial y}\} + Q - S \frac{\partial \phi_b}{\partial t} \qquad (38)$$

  In general, $R \neq 0$. The coefficients ϕ_i of the approximate solution ϕ_b are now chosen in such a way that R is a minimum. This can be done in many ways. The most well known method is that of Galerkin. In This method R is minimized by making R orthogonal to the basic function L_i, i.e.

  $$\iint_G RL_i \, dG = 0 \quad i = 1,N \qquad (39)$$

  The integration is again done element by element. When the derivative with respect to time (37) is made discrete, (39) again forms a system of N linear equations in the N unknown ϕ_i's.

  These can be solved by well known methods.

Boundary conditions

The initial condition is introduced by starting with known value ϕ. Boundary conditions can be used without any problem in the finite element method.
The integrations (34) and (39) required are carried out using the Green integral theorem (Kreyszig, 1972), as a result of which the flow across the boundary of the area under consideration enters into the equation directly.

In the case of a fixed potential at the boundary, the potentials in the mesh-points in the linear equations (36) and (39) are kept constant at the boundary and the flow across the boundary is calculated. In the case where the flow at the boundary is given, this flow is substituted in the equations and the potential at the boundary mesh-points is calculated.

3. COMPUTER SOFTWARE

3.1. Introduction

In the computer processing of data, two types of software are encountered: record-compiling software and computing software. Record-compiling software is encountered when only the collection and administration of data is involved. In that case the data are stored on a disc memory or on a magnetic tape. The computer programme provides for the administration and can be used to add, change or remove data. Such software can be of importance if a large quantity of data (for example, piezometer measurements) have to be processed. In such a case it is of importance that the organisation of the data file is designed so that any information required can be extracted from the file in a simple manner. The output obtained should be set out in such a way that it is readily understood and can be used for further processing (e.g. in other computer models).

The software for further processing should in turn interface well with the organizational structure of the data files so that an optimum result can be obtained with little effort on behalf of the user. The record-compiling software will not be dealt with further in this report.

3.2. Computing software

The second group of software which is of importance is used for carrying out calculations. These are sometimes statistical calculations using the information stored in the data files. Mostly, they concern simulation of the groundwater flow. The amount of data used for this purpose may vary widely. Computer programmes used to simulate, for example, groundwater flow with the aid of piezometer measurements over a large area, will in general make use of a large amount of data. As a result of such a simulation detailed information can be obtained on the distribution of piezometric heads, and flow intensities. Such a case may involve simulation of flow in an existing or previous situation, or a forecast. With other computer programmes it is possible, starting from basic data (such as the geometry of an area and its permeability properties), to simulate an imaginary flow. As a rule, much less data are necessary for such programmes than in the preceding case because basic data are in general much less numerous than piezometric head measurements. The measurements on the imaginary flow diagram (calculation results) may again be used, if desired, to relate calculated and measured quantities to one another. A clearer insight is thereby gained into the geohydrological properties of a given area.

Computer software which allows imaginary situations to be simulated can provide an important set of tools in both qualitative and quantitive control of groundwater. By simulating imaginary situations the person undertaking the control is in a better position to confirm the consequences of control measures. Such software can also be useful in studying the causes of problems which arise. Also, by varying the parameters, different types of flow can be simulated to explain observed phenomena. On this basis the person undertaking the control can then take effective measures.

In assessing computer programmes from the user's point of view, both separate programmes and programme packages can be considered. A programme package is a collection of coherent computer programmes which can be used as a whole or in part, depending on the nature of the problem. The final choice of a given programme or programme package will be influenced by the following factors:

efficiency:

first of all, the user will wish to assess to what extent a computer programme can provide an early answer to his specific questions;

standardization required:

the user's preference will generally be for software which will allow him to process his data as fully as possible and which does not first of all require him to carry out data preparation operations.

accuracy:

this must be viewed in the light of the accuracy of the input data: if, for example, the c-values are only known with an accuracy of 10 - 20%, there is no point in carrying out calculations which yield seepage figures to an accuracy of 1%;

reliability:
by reliability is meant the capacity of the programme to actually solve all the problems for which it should, in principle, be suitable. It will be dangerous if incorrect results are obtained in cases which are not specifically excluded in the documentation of the scope of application.

time:

the time which elapses between the setting of a given problem and the obtaining of a solution can depend, apart from on the problem itself, also on the computer software. For the quantity of input and consequently the quantity of checking work required on the input, can vary considerably for each programme;

location:
a package that needs all the other user requirements but is inaccessible in practice has no value for the user;

costs:
the costs are generally weighed up against the importance of solving a specific problem. ("What is the user prepared to pay").

support;
the support given to the user in using the computer programme and in any problems which may arise, can be of importance; for big and complicated programmes good support is particularly essential;

documentation:
good documentation, describing the aspects mentioned above, is an important aid in the choice and use of a suitable programme.

In addition to these general user aspects there are several computer-engineering aspects, which may be of importance to the user. The amount of memory storage required and the computing time, in particular, may decide whether a programme is always available or can only be used during certain hours of the day.

In many cases it is true that a user, who has to deal with various problem types, has a preference for a model which has as general an applicability as possible. This is usually based on one of the numerical computation techniques dealt with in chapter 2.3 (Method of solution). The following points may serve as a guide for gaining an insight into the general applicability of a computer programme.

- Number of dimensions:
  those programmes are the most general which can describe a three-dimensional flow. Hitherto such computer programmes have been rare. However, in many cases a two-dimensional model will suffice for the user; in some cases a one-dimensional calculation is satisfactory. It is important that the "comfort" offered by a model (for example, a small amount of input work) remains unchanged if a different number of dimensions is used. A three-dimensional model, for example, only offers equal "comfort" as a two-dimensional model with a good network generator if, within arbitrary spatial boundaries, spatial elements can automatically be generated without extra manual work arising.

- Arbitrarily shaped flow regions :
  these can, in general, certainly be calculated with the numerical computational techniques specified in chapter 2.3 (Methods of solution). The amount of input work demanded from the user can then vary considerably. The use of a good network generator can reduce the amount of input work enormously. In the assessment, however, account should be taken of the extent to which these can also generate necessary refinements of an element network in part of the flow region (near sinks and sources).

Anisotrophy:
this means that the permeability depends on direction. In Dutch circumstances the permeability in the horizontal direction is often greater than in the vertical direction. It may be important for the computer programme to take into account anisotropy in any direction.

Inhomogeneities:
these often arise in the form of alternations of clay, peat and sand layers or through variations in the permeability of a sand formation. Relatively thin, but nevertheless resistive clay and silt layers may also occur (for example, on the banks and beds of water courses or between different sand formations). The forming of cracks can also produce an extra complication. An indication can be given of the extent to which a computer programme can allow for this type of inhomogeneity and if there are limitations with regard to the maximum differences in permeability, etc.

Sinks and sources:
the presence of sinks and sources will in general cause no problems in the calculation. Their presence, as already mentioned, can have an influence on the desired element distribution within a region and, consequently, sometimes on the amount of input work to be done.

Several fluids:
for calculations involving fresh and salt water, a model should permit computation with several fluids. In multiple fluid problems a distinction is made between the flow of a fluid which is contiguous with a stationary fluid (usually salt water) and flow involving the simultaneous movement of two or more fluids. It may also be necessary for the computer programme to take into account gradual changes in the density of the fluid.

Non steady flow:
this primarily plays a role in the case of phreatic water flow, flow in compressible layers and flow involving several fluids. It is generally true that programmes suitable for non steady computations can also be used to calculate a steady state.

Multi-layer systems:
these are systems in which the flow can be represented as semi-three-dimensional. In this case a number of horizontal sand layers in the aquifer are separated by resistive clay and peat layers. In each of the horizontal sand layers the flow is practically two-dimensional. Between the sand layers mutual interchange of water occurs as a result of practically vertical flow through the resistive layers.

- For all the models it can be specified whether the flow occurs in the saturated or in the unsaturated zone or whether both flows are perhaps combined. It can further be specified for the models whether, and indeed to what degree, a link with other models is possible (agricultural models, economic models, etc.).In certain cases it may also be of importance that a computer programme readily offers the facility for carrying out sensitivity analyses in relation to the decisive parameters of the problem.

- The number of operations that the user must carry out to obtain the result is of importance for the manner of use. This includes the data preparation work required. If a network generator is used, the quantity of input work is generally very much reduced. Sometimes it is still necessary to exercise a visual control on the network generated by first examining a(automatically prepared) drawing and making some alterations if necessary in the element numbering. It becomes appreciably more complicated if the surroundings of sinks and sources or certain parts of the flow area require network refinements. Some network-generators will be able to tackle such problems without difficulty; in other cases time-consuming extra work has to be done to adapt the element-network in the required manner.

- The facility the user has for storing data which result from a computation or from measurements is also of importance in the manner of use. In particular, where measurement results are involved, he would be interested in the existence of auxiliary software (these are other components of a programme package) allowing series of measurements to be tested and correlated.

- Closely connected with the manner of use are the costs. These are strongly problem-dependent; they are moreover connected with the degree of data preparation. Costs are further influenced by the method of computation used in the programme. In particular, in the case of non steady flow the permissible value of the time step has a large effect. However, the percentage overhead charges applied to the computing costs are also often a very decisive factor from the point of view of price. This overhead contains development costs and a profit percentage. It can vary from zero to 1000%, or more in extreme cases.

- By the transferability of a computer programme is meant the extent to which the programme can be used on different computers without special provisions. This aspect is of importance because many computers have special extra provisions in relation to programming which other computers do not have or have in modified form. Such a programme can in general be transferred less readily and these extra provisions will have to be adapted if a different computer is used. Computer programmes which make no use of such special facilities and which are programmed in a standard language are in general easily transferable.

- By the term maintenance of the computer is meant the operations which have to be carried out if something is not working properly (programme-oriented maintenance), or if something in the computer system is modified.

- Of more importance for the use is the above mentioned aspect of the memory requirements and computing time needed for the programme. If these are very large, there is a good chance that the use of the programme will lead to conflicts with other activities on the computer because the demand placed on its capacity is too great. Often in such cases it will only be possible to carry out computations at times when there are significantly fewer other users, for example, at night or at weekends. Computer programmes which require relatively little memory space and computing time have an advantage in this connection, since often they allow results to be obtained during the day within a very short time.

4. SURVEY RESULTS

4.1 Range of requirements

Table 2 presents a survey of the most important human activities and the conditions applying to them which relate to water management, the emphasis being on groundwater control. It is evident from the table that measures taken with respect to one activity may effect another activity, often in an unfavourable way. As a result, in many cases it is necessary to compare conflicting interests. Such a comparison of interests can only be done by quantifying the effects and side effects of intervention in water management. In this respect research will have to take place through mutual contact at a national, regional and local level.

At national level this research is concerned mainly with the distribution of surface water, in which the interests of shipping, salination prevention, agriculture, drinking and industrial water supply play a large role. It will be clear that the control of national waters is an important boundary condition for regional groundwater control. This is true both for periods of severe drought and for periods of water excess.

In general, water balance studies relating to water management such as extraction possibilities etc, and research for the benefit of provincial groundwater policy are of a regional nature.

Local research is concerned with extraction or infiltration, draining, sand removal, well draining etc., and measures have to be drawn up to compensate for damage resulting from these activities.

In the course of the surveys, it became clear that the users did not know what is expected in the field of groundwater models. This applies not so much to the local level (the working out of pumping test results, pumping station calculations etc.) as to the regional and national level.

Table 3 summarizes the answers to the first five questions of the questionnaires relating to the requirements placed on groundwater models. No conclusions can be drawn from the answers to the remaining questions of this questionnaire (see Appendix 2) because they are of too fragmentary a nature and in many cases were actually missing.

Table 2

1	2	3	4	5	6	7	8	9
Activity	Conditions	Measures, operations	Main effects	Influence on other activities	Activities carried out by:	Management approval, financial support	Policy preparation	Policy consolidating research
Habitation, traffic	Dry	Polder construction, polder-removal, sewering, dyking, sand-extraction, well draining	Drop in groundwater level	Agriculture, drinking and industrial water supply, nature control	Government, province, local authority, water board	Government, province, local authority, water board	Government province, local authority. water boards, water co.s	Govt. services, institutes, consulting engineers, universities/ technical schools
Agriculture	Optimum groundwater level	Polder building, river regulation, weirs, ditches, dykes, watering; using groundwater, using surface water, water inlet draining	Level control higher or lower groundwater level	Drinking and industrial water supply, nature control, shipping	Water board, farmers	Government, province, water board		
Drinking & industrial water supply	Quality quantity	Water extraction points, protected zones, infiltration	Drop or rise in water level	Agriculture, nature control, shipping, habitation (through increase in no. of wells and sand extraction)	Water companies, industry	Government, province, water board		

CONT/over...

1	2	3	4	5	6	7	8	9
Activity	Conditions	Measures, operations	Main effects	Influence on other activities	Activities carried out by:	Management approval, financial support	Policy preparation	Policy consolidating research
Shipping	Open water level	Weirs, sluices, canals, dykes, sand extraction, well draining	Higher or lower ground water level, seepage	Agriculture, drinking & industrial water supply, nature control	Government, province, water board	Government, province, water board		
Nature control	Conservation	Acquisition and control of sites		Agriculture, drinking & industrial water supply, habitation, shipping	Government, private organisations	Government, province		

Table 2: Review of the activities and conditions relating to groundwater control

Table 3. Answers to some of the questionnaires from users.

Question 1: Why do you think you need the model?

A. Policy questions

Drawing up recommendations on groundwater extraction.
Setting up damage controls.
Water control extractable groundwater relationship.
Preparation for water control activities.
Determination of internal and external limitations on water supply possibilities.
Level control relationship for built up area - agricultural area.
Influence on water management measures or water extraction on natural regions.
Measures to overcome such influences.
Soil improvement recommendations.
Effect of groundwater level change on the use characteristics of the soil.

B. Type of questions

Influence on agricultural crop production - natural areas.
Salinization of ground and surface water.
Hydrological boundaries.
Infiltration/quality relationship for groundwater.
Precipitation/run-off relation, basic run-off.
Protected zones at water extraction locations.
Groundwater level/ecosystems relation, among other things, through soil physical quantities.
Draining of excavated building sites, drainage.
Infiltration of effluent water.
Load on geo-technical constructions.
Pressure waves in water during pile-driving.

Table 3 continued

C. Type of problems

Groundwater level analysis.
Water balance.
Subsidence.
Goundwater/run-off relationship for precipitation, or supply/agricultural production.
Distance of tube drains/ditches.
Weirs - ditch levels.
Influence of groundwater extraction.
Fast processes (wave penetration).
Contruction problems (dyke building).
Pump test simulation.
Seepage.
Non steady groundwater flow.
Salt water displacement through well infiltration.
Flow in immediate neighbourhood of wells.

D. Model engineering

Data storage, processing, statistics.
Sensitivity analysis in relation to boundary conditions.
Time-variable boundary conditions.
Three-dimensional models.
Multi-layer flow.

Table 3 (continued)

Question 2: For what scale must the model be suited?
Varies from very localized to (if possible) national.
Question 3: What is your policy/control field, or study/ research field?
Surface water control. Groundwater control. Influence on agricultural and natural areas. Salinization. Hydrological boundaries. Subsidences. Well draining. Protected zones for water extraction areas. Financial support for Water Department activities. Set up and scope of water extraction. Drinking water supply. Artificial sub-irrigation/infiltration. Influence of groundwater flow on stability of dykes.
Question 4: In what time scale do you expect and answer?
Varies from several days to approximately one year.

Table 3 (continued)

Question 5: What must the model be able to simulate (output needed)?
Groundwater levels, contour lines.
Groundwater flow, steady and non-steady.
Run-off, seepage.
Sub-irrigation/infiltration, percolation.
Geo-hydrological soil constants.
Potentials in clay formations.
Distribution of piezometric heads.
Overpressures beneath dyke cladding.
Phreatic storage and elastic storage.
Damping and penetration of waves.
Three-dimensional flow.
Inhomogeneities.
Anisotropy.
Wells and bore holes.
Axially symmetrical problems.
Simultaneous flow of several fluids.
Intensities of flow.
Influence of evapo-transiration and precipitation.
Moisture content, moisture tension, capillary rise.
Salt content.
Interaction of ground - and surface water.
Evapotranspiration.
Determination of location of fresh/salt boundary.

4.2 Existing software

The survey carried out by the ad-hoc group among the designers of groundwater models has provided a large amount of information regarding the groundwater models in use in The Netherlands. This information is reproduced in Tables 4 to 16 inclusive.

Table 4 gives a summary of the existing groundwater models, grouped as follows:

- models for saturated flow;
- models for unsaturated flow;
- models for saturated-unsaturated flow

Each group is divided into sub-groups for steady and non steady groundwater flow. As far as necessary, a further sub-division into one- two- or three-dimensional groundwater flow is made. This classification has been chosen because, in view of the results of the requirements survey, it was not possible to give a problem-oriented classification.

The individual models are always featured in the group which provides the widest application possibilities. Thus, two- or three-dimensional models will generally also be suitable for computing one- or two-dimensional flows respectively. Likewise, non steady models can generally be used for computing steady flows.

Each of the headlines in Tables 5 to 15 inclusive give detailed information on the models with regard to input data, initial and boundary conditions, output, testing, some computer-engineering aspects and availability. Information is only included if it is relevant for the table in question. Thus, for example, the initial-conditions heading is not included in the table for steady-flow models.

The following notes should be added to the data given in the tables:

- the survey of existing groundwater models is only a momentary record with a final date of 30 June 1977;
- the information used in the tables has been obtained directly from the institutions surveyed, and accepted by the ad-hoc group without question.
- a distinction is made in the tables between conditional and unconditional availability. By conditional availability is meant that the models can only be used under the conditions set by the institutions concerned;
- quite a large number of models are similar to each other and probably stem from the same basic model. Since the task of the ad-hoc group was only one of collecting information, these models have been accepted as separate ones, if classed as such by the institutions surveyed.

- no information has been recorded as regards computing costs. These costs are so strongly problem-dependent, that hardly anything can be said about them. In addition, these costs are expected in general to be relatively low as compared with the costs incurred in collecting the input data.

Finally, Appendix 4 gives a concise description of the models, together with the contact for these models in the various institutions.

saturated	steady	2-dim.	hor.	LM1;LM4(IWA124);IWA139;THEO; IWA132: ICW1; ICW3; FLOP1; FLOP2	see table 5
			vert.	IWA153; RWRO1(RWRO6); WIDMOS; ICW2; AGSO3	see table 6
		3-dim.		STATRECT-2; TRIST; IWA135(IWA136); v.d.Akker(ALMERE); WL/W316-1	see table 7
	non-steady	2-dim.	hor.	MOTGRO; ILRI1; FRONT; HEIDEMY1; WL/S135-1; TYSON	see table 8
			vert.	MOTGRO; IWA154;LM6(IWA128); MUFLO3/4; RWRO3 (RWRO5; RWRO8; RWR10; RWR12; RWR13); WL/S135-2; AGSO1 (AGSO2)	see table 9
		3-dim.		SEEP, TRANSRECT-2; v.BAKEL	see table 10
unsaturated	steady	1-dim.	vert.	CAP.OPST.; WL/S349-1	see table 11
	non-steady	1-dim.	vert.	HEIDONS; FLOW; FEDDES;SOILWAT; v.KEULEN; WL/S349-2	see table 12
combined (saturated-unsaturated)	steady	2-dim.	vert.	BOELS	see table 13
	non-steady	1-dim.	vert.	MAKKINK-v.HEEMST	see table 14
		2-dim.	vert.	UNSAT-2; MM2	see table 15
		3-dim.		de LAAT- v.d. AKKER(SUM2,WL/S349-3)	see table 16

Table 4. Review of existing groundwater models

Table 5. Models for saturated, steady, two-dimensional flow in a horizontal plane

		LM 1	LM 4 (IWA 124)	IWA 139	THEO	FLOP 1	FLOP 2	IWA 132	ICW 1	ICW 3
INPUT										
Hydrological properties	Permeability	+	+	+	+	-	+	+	+	+
	Inhomogeneity	+	+	-	+	-	-	+	+	-
	Anisotropy	-	-	-	-	-	-	-	-	-
	Thickness of water-bearing formation	+	+	+	+	+	+	+	+	+
	Resistence of low-permeability layer	-	-	+	-	-	+	-	-	-
	Storage coefficient/ effective porosity	-	-	-	-	+	+	-	-	-
	Entrance/radial resistance	-	-	-	-	-	-	-	-	-
	Drainage resistance	-	-	-	-	-	-	-	-	-
Boundary conditions	Potential	+	+	-	+	-	-	+	+	+
	Impermeable boundary	+	+	-	+	-	-	+	-	+
	Flux across boundary	-	-	-	+	-	-	+	-	-
	Point extraction/infiltration	-	+	+	+	+	+	+	-	+
	Effective precipitation	-	-	+	+	-	-	+	-	+
	Natural groundwater flow	-	-	-	-	+	+	-	-	-
Network generation		-	-	-	+	-	-	-	-	-
OUTPUT										
Hydrological data	Potential	+	+	-	+	-	-	+	+	+
	Flux	-	-	-	+	-	-	+	+	-
	Point extraction/infiltration	-	-	-	-	-	-	+	-	-
	Discharge to drains	-	-	-	-	-	-	-	-	-
	Stream lines	-	-	+	-	+	+	-	-	-
	Equipotential lines	-	-/+	-	+	-	-	-	-	-
	Travel time	-	-	+	-	+	+	-	-	-
	Water Balance	-	-	-	-	-	-	+	+	-
Form of output plot	Print	+	+	+	+	+	+	+	+	+
	Plot	-	-/+	+	+	+	+	-	-	-

Table 5 continued

		LM 1	LM 4 (IWA 124)	IWA 139	THEO	FLOP 1	FLOP 2	IWA 132	ICW 1	ICW 3
OUTPUT										
Sensitivity analysis		-	-	+	-	-	-	+	-	-
Testing	Analytical solution	+	+/-	-	+	+	+	-	+	+
	Field measurement	-	-	-	+	-	-	-	+	-
	Scale model	-	-	-	-	-	-	-	-	-
Computation method	Finite differences	-	-	-	-	-	-	-	+	-
	Finite elements	+	+	-	+	-	-	+	-	+
	Runga Kutta	-	-	+	-	+	+	-	-	-
Computer	IBM	+	+	-	+	+	+	-	-	-
	CDC/Cyber	-	-	+	+	+	+	-	-	-
	DEC	-	-	-	-	-	-	-	+	+
	Honeywell Bull	-	-	+	-	-	-	+	-	-
Language	Fortran	+	+	+	+	+	+	+	+	+
	Algol	-	-	-	-	-	-	-	+	-
Availability	Conditional	-	-	+	+	-	-	+	-	-
	Unconditional	+	+	-	-	+	+	-	+	+
Operating manual	System	-	-	+	-	-	-	+	+	+
	User	-	-	-	-	+	+	-	+	+

Table 6. Models for saturated, steady, two-dimensional flow in a vertical plane

		IWA 153	RWR01 (RWR06)	WIDMOS	ICW 2	AGS 03
INPUT						
Hydrological properties	Permeability	+	+	+	+	+
	Inhomogeneity	−	+/−	+	−	−
	Anisotropy	−	−	−	−	−
	Thickness of water bearing formation	+	+	−	+	+
	Resistance of low-permeability layer	+	−	−	−	−
	Storage coefficient/effective porosity	−	+	−	−	+
	Entrance/radial resistance	−	−	+	−	−
	Fresh/salt	+	−	−	−	−
Boundary conditions	Potential	+	+	+	+	+
	Impermeable boundary	−	+	−	+	+
	Flux across boundary	−	+	−	−	−
	Point extraction/infiltration	+	−	−	−	−
	Effective precipitation	+	+	−	−	+
	Fresh/salt boundary plane.	+	−	−	−	−
Network generation		−	−	−	+	−
OUTPUT						
Hydrological data	Potential	+	+	+	+	+
	Flux	−	+	+	−	−
	Point extraction/infiltration	+	−	−	−	−
	Discharge to drains	−	−	+	−	−
	Stream lines	−	−	−	−	−
	Equipotential lines	−	−	−	−	−
	Travel time	−	−	−	−	−
	Water balance	−	+	−	−	−
	Fresh/salt boundary plane	+	−	−	−	−
Form of output plot	Print	+	+	+	+	+
	Plot	−	+	−	−	+

Table 6. continued

		IWA 153	RWR01 (RWR06)	WIDMOS	ICW 2	AGS 03
OUTPUT						
Sensitivity analysis		+	-	+	-	-
Testing	Analytical solution	+	+	-	+	+
	Field measurement	+	-	-	-	-
	Scale model	+	-	-	-	-
Computation method	Finite differences	+	+	+	+	+
Computer	DEC	-	+	+	+	+
	Honeywell Bull	+	-	-	-	-
Language	Fortran	+	+	+	+	+
Availability	Conditional	+	-	-	-	-
	Unconditional	-	+	+	+	+
Operating manual	System	+	-	+	+	-
	User	-	-	-	+	-

Table 7. Models for saturated, steady, three-dimensional flow

		STATRECT-2	TRIST	IWA 135 (IWA 136)	v.d.Akker (ALMERE)	WL/W316-1
INPUT						
Hydrological properties	Permeability	+	+	+	+	+
	Inhomogeneity	+	+	+	+	–
	Anisotropy	–	–	–	–	–
	Thickness of water bearing formation	+	+	+	+	+
	Resistance of low-permeability layer	+	+	+	+	–
	Entrance/radial resistance	+	+	–	+	–
	Drainage resistance	+	+	–	–	–
	Fresh/salt	–	–	+	–	–
Boundary conditions	Potential	+	+	+	+	+
	Impermeable boundary	+	+	+	+	+
	Flux across boundary	–	+	+	+	–
	Point extraction/infiltration	+	+	+	+	–
	Effective precipitation	+	+	+	+	–
	Fresh/salt boundary plane	–	–	+	–	–
Network generation		–	+	+	–	–
OUTPUT						
Hydrological data	Potential	+	+	+	+	+
	Flux	+	+	+	+	+
	Point extraction/infiltration	+	–	–	–	–
	Discharge to drains	+	+	–	+	–
	Stream lines	–	–	–	–	+
	Equipotential lines	+	+	–	–	+
	Travel time	–	–	–	–	–
	Water balance	+	+	+	+	–
	Fresh/salt boundary plane	–	–	+	–	–
Form of output	Print	+	+	+	+	+
	Plot	+	+	–	–	–

Table 7 continued

		STATRECT-2	TRIST	IWA 135 (IWA 136)	v.d.Akker (ALMERE)	WL/W316-1
Sensitivity analysis		+	-	+	-	+
Testing	Analytical solution	-	-	-	-	+
	Field measurement	-	-	+	+	-
	Scale model	+	-	-	-	-
Computation method	Finite elements	+	+	+	+	-
	Source covering	-	-	-	-	+
Computer	IBM	+	+	-	-	-
	CDC/Cyber	-	-	-	+	+
	Honeywell Bull	-	-	+	-	-
Language	Fortran	+	+	+	+	+
Availability	Conditional	+	+	+	-	+
	Unconditional	-	-	-	+	-
Operating manual	System	-	-	+	-	-
	User	-	-	-	-	-

		MOTGRO	ILRI 1	FRONT	HEIDEMY 1	WL/S135-1	TYSON
INPUT							
Hydrological properties	Permeability	+	+	+	+	+	+
	Inhomogeneity	+	+	-	+	+	+
	Anisotropy	+	-	-	-	-	+
	Thickness of water bearing formation	+	+	+	+	+	+
	Resistance of low-permeability layer	+	-	-	-	-	-
	Storage coefficient/effective porosity	+	+	+	+	+	+
	Entrance/radial resistance	+	-	-	+	-	-
	Drainage resistance	+	-	-	+	-	+
	Fresh/salt	+	-	-	-	-	-
Initial conditions	Potential	+	+	-	+	+	+
Boundary conditions	Potential	+	+	-	+	+	+
	Impermeable boundary	+	+	-	+	+	-
	Flux across boundary	+	+	-	+	+	+
	Point extraction/infiltration	+	+	+	+	+	+
	Effective precipitation	+	+	-	+	+	+
	Fresh/salt boundary plane	+	-	-	-	-	-
	Natural groundwater flow	-	-	+	-	-	-
Network generation		-	-	-	-	-	-
OUTPUT							
Hydrological data	Potential	+	+	-	+	+	+
	Flux	+	+	-	+	+	+
	Point extraction/infiltration	+	+	-	-	-	-
	Discharge to drains	-	-	-	+	-	+
	Stream lines	-	-	+	-	-	-
	Equipotential lines	-	-	-	-	+	-
	Travel times	-	-	+	-	-	-
	Water balance	+	+	-	+	+	+
	Fresh/salt boundary plane	+	-	-	-	-	-

Table 8 continued

		MOTGRO	ILRI 1	FRONT	HEIDEMY 1	WL/S135-1	TYSON
OUTPUT							
Form of output	Print	+	+	+	+	+	+
	Plot	-	-	+	-	+	-
Sensitivity analysis		+	+	-	-	+	-
Testing	Analytical solution	+	-	+	-	+	-
	Field measurement	-	+	-	-	-	+
	Scale model	-	-	-	-	-	-
Computation method	Finite differences	-	+	-	+	-	+
	Finite elements	-	-	-	-	+	-
	Analytical functions	+	-	-	-	-	-
	Runga Kutta	-	-	+	-	-	-
Computer	IBM	+	+	+	-	-	-
	CDC	-	+	-	+	+	-
	P1400	+	-	-	-	-	-
	DEC	-	-	-	-	-	+
	PDP	-	+	-	-	-	-
Language	Fortran	+	+	+	+	+	+
Availability	Conditional	+	-	-	+	+	-
	Unconditional	-	+	+	-	-	+
Operating manual	System	-	+	-	+	+	-
	User	+	-	+	-	+	+

Table 9: Models for saturated, non-steady, two-dimensional flow in vertical plane

		MOTGRO	IWA 154	LM6 (IWA128)	MUFLO3/4	RWR03 (RWR05, RWR08 RWR10, RWR12, RWR13)	WL/S135-2	AGS01 (AGS02)
INPUT								
Hydrological properties	Permeability	+	+	+	+	+	+	+
	Inhomogeneity	+	-	+	-	+	+	-
	Anisotropy	+	-	-	-	-	-	-
	Thickness of water bearing formation	+	+	+	+	+	-	+
	Resistance of low-permeability layer	+	+	-	-	-	-	-
	Storage coefficient/effective porosity	+	-	+	-	+	+	+
	Entrance/radial resistance	+	-	-	-	-	-	-
	Fresh/salt	+	+	-	+	-	-	-
Initial conditions	Potential	+	+	+	+	+	+	+
Boundary conditions	Potential	+	+	+	+	+	+	+
	Impermeable boundary	+	-	+	+	+	+	+
	Flux across boundary	+	-	-	-	+	-	-
	Point extraction/infiltration	+	+	-	+	-	-	-
	Effective precipitation	+	+	-	-	+	-	+
	Fresh/salt boundary plane	+	+	-	+	-	-	-
Network generation		-	-	-	-	-	-	-
OUTPUT								
Hydrological data	Potential	+	+	+	-	+	+	-
	Flux	+	-	+	-	+	-	-
	Point extraction/infiltration	+	+	-	-	-	-	-
	Discharge to drains	-	-	-	-	+	-	-
	Stream lines	-	-	-	-	-	-	-
	Equipotential lines	-	-	-	-	-	-	-
	Travel time	-	-	-	-	-	-	-
	Water balance	+	-	-	-	-	-	-
	Fresh/salt boundary plane	+	+	-	+	-	-	-
Form of output	Print	+	+	+	+	+	+	+
	Plot	-	-	-	-	+	-	+

Table 9 continued

		MOTGRO	IWA 154	LM6 (IWA128)	MUFLO3/4	RWR03 (RWR05, RWR08 RWR10, RWR12 RWR13)	WL/S135-2	AGS01 (AGS02)
OUTPUT								
Sensitivity analysis		+	+	−	−	−	+	−
Testing	Analytical solution	+	−	+	−	+	+	+
	Field measurement	−	−	−	−	−	−	−
	Scale model	−	+	−	+	−	−	−
Computation method	Finite differences	−	+	−	−	+	−	+
	Finite elements	−	−	+	−	−	+	−
	Analytical functions	+	−	−	−	−	−	−
	Vortices	−	−	−	+	−	−	−
Computer	IBM	+	+	+	+	−	−	−
	CDC/Cyber	−	−	−	−	−	+	−
	P1400	+	−	−	−	−	−	−
	DEC	−	−	−	−	+	−	+
	Honeywell Bull	−	+	+	+	−	−	−
Language	Fortran	+	+	+	+	+	+	+
Availability	Conditional	+	+	−	−	−	+	−
	Unconditional	−	−	+	+	+	−	+
Operating manual	System	−	+	−/+	−	−	+	−
	User	+	−	−	−	−	−	−

Table 10: Models for saturated, non-steady, three-dimensional flow

		SEEP	TRANSRECT-2	VAN BAKEL
INPUT				
Hydrological properties	Permeability	+	+	+
	Inhomogeneity	+	+	+
	Anisotropy	+	–	–
	Thickness of water bearing formation	+	+	+
	Resistance of low-permeability layer	+	+	–
	Storage coefficient/effective porosity	+	+	+
	Entrance/radial resistance	–	+	–
	Drainage resistance	–	+	–
	Fresh/salt	+	–	–
Initial conditions	Potential	+	+	+
Boundary conditions	Potential	+	+	+
	Impermeable boundary	+	+	+
	Flux across boundary	–	–	+
	Point extraction/infiltration	+	+	+
	Effective precipitation	+	+	+
	Fresh/salt boundary plane	+	–	–
Network generation		+	–	–
OUTPUT				
Hydrological data	Potential	+	+	+
	Flux	–	+	–
	Point extraction/infiltration	+	+	–
	Discharge to drains	–	+	–
	Stream lines	+	–	–
	Equipotential lines	+	+	–
	Travel time	+	–	–
	Water balance	+	+	–
	Fresh/salt boundary plane	+	–	–
Form of output	Print	+	+	+
	Plot	+	+	–

Table 10 continued

		SEEP	TRANSRECT-2	VAN BAKEL
OUTPUT				
Sensitivity analysis		–	+	–
Testing	Analytical solution	+	–	+
	Field measurement	+	–	–
	Scale model	–	–	–
Computation method	Finite differences	–	–	+
	Finite elements	+	+	–
Computer	IBM	+	+	–
	P1400	+	–	–
	DEC	–	–	+
	PDP	+	–	–
Language	Fortran	+	+	+
Availability	Conditional	+	+	–
	Unconditional	–	–	+
Operating manual	System	+	–	–
	User	+	–	–

Table 11: Models for unsaturated, steady, one-dimensional vertical flow

		CAP. OPST.	WL/S349-1
INPUT			
Hydrological properties	Permeability	+	-
	Inhomogeneity	+	-
	Unsaturated permeability	+	+
	Moisture tension	+	+
	Root zone	-	-
Boundary conditions	Potential	+	-
	Moisture content/tension	+	+
	Potential evapotranspiration	-	+
	Precipitation	-	+
OUTPUT			
Hydrological data	Potential	-	-
	Flux	-	-
	Point extraction/infiltration	-	-
	Moisture content/infiltration	+	+
	Actual evapotranspiration	-	-
	Capillary flux through phreatic surface	+	-
	Water balance	+	-
Form of output	Print	+	+
	Plot	-	+
Sensitivity analysis		-	+
Testing	Analytical solution	-	-
	Field measurement	+	-
	Scale model	-	-
Computation method	Finite differences	+	-
	Runga Kutta	-	+
Computer	CDC/Cyber	+	+
Language	Fortran	+	+

Table 11 continued

		CAP. OPST.	WL/S349-1
OUTPUT			
Availability	Conditional	-	+
	Unconditional	+	-
Operating manual	System	+	+
	User	-	+

Table 12: Models for unsaturated, non-steady, one-dimensional vertical flow

		HEIDONS	FLOW	FEDDES	SOILWAT	VAN KEULEN	WI/S349-2
INPUT							
Hydrological properties	Permeability	+	+	+	+	-	-
	Inhomogeneity	+	+	-	+	-	-
	Unsaturated permeability	+	+	+	+	-	+
	Moisture tension	+	+	+	+	+	+
	Root zone	+	-	+	+	+	-
Initial conditions	Potential	+	+	+	+	-	-
	Moisture content/tension	-	+	+	+	+	+
Boundary conditions	Potential	+	-	+	+	-	-
	Moisture content/tension	+	-	+	+	+	+
	Potential evapotranspiration	+	-	+	+	+	+
	Precipitation	+	+	+	+	+	+
OUTPUT							
Hydrological data	Potential	+	+	-	-	-	-
	Flux	-	+	+	+	-	+
	Point extraction/infiltration	-	-	+	+	+	-
	Moisture content/tension	-	+	+	+	+	+
	Acutal evapotranspiration	+	-	+	+	+	-
	Capillary flux through the phreatic surface	-	+	+	+	-	+
	Water balance	-	+	+	+	+	+
Form of output	Print	+	+	+	+	+	+
	Plot	-	-	-	-	+	+
Sensitivity analysis		-	+	+	+	+	+
Testing	Analytical solution	-	+	-	-	-	-
	Field measurement	-	+	+	+	+	-
	Scale model	-	+	-	-	-	-
Computation method	Finite differences	+	+	+	+	+	+
Computer	IBM	-	-	+	+	+	-
	CDC/Cyber	+	+	+	+	-	-
	DEC	-	-	-	-	+	-
	PDP	-	+	-	-	-	-
Language	Fortran	+	+	+	+	-	+
	CSMP	-	-	-	-	+	-

Table 12 continued

		HEIDONS	FLOW	FEDDES	SOILWAT	VAN KEULEN	WL /S349-2
OUTPUT							
Availability	Conditional	-	-	-	-	-	+
	Unconditional	-	+	+	+	+	-
Operating manual	System	-	-	-	-	+	+
	User	+	-	-	-	+	-

Table 13: Models for combined, steady, two-dimensional flow in a vertical plane

		BOELS
INPUT		
Hydrological properties	Permeability	+
	Inhomogeneity	-
	Anisotrophy	+
	Thickness of water bearing information	+
	Resistance of low permeability layer	-
	Storage coefficient/effective porosity	-
	Unsaturated permeability	+
	Moisture tension	-
	Entrance/radial resistance	-
	Fresh/salt	-
	Root zone	-
Initial conditions	Potential	+
	Moisture content/tension	-
Boundary conditions	Potential	+
	Impermeable boundary	+
	Flux across boundary	-
	Point extraction/infiltration	-
	Moisture content/tension	-
	Potential evapotranspiration	-
	Precipitation	+
	Fresh/salt boundary plane	-
Network generation		-
OUTPUT		
Hydrological data	Potential	+
	Flux	+
	Point extraction/infiltration	-
	Moisture content/tension	+
	Actual evapotranspiration	-
	Capillary flux through phreatic surface	+
	Discharge to drains	-
	Stream lines	-
	Equipotential lines	-
	Travel time	-
	Water balance	+
	Fresh/salt boundary plane	-

Table 13 continued

		BOELS
OUTPUT		
Form of output	Print	+
	Plot	-
Sensitivity analysis		-
Testing	Analytical solution	+
	Field measurement	-
	Scale model	-
Computation method	Finite differences	+
Computer	CDC/Cyber	+
Language	Fortran	+
Availability	Conditional	-
	Unconditional	+
Operating manual	System	-
	User	-

Table 14: Models for combined, non-steady, one-dimensional vertical flow.

		MAKKINK/VAN HEEMST
INPUT		
Hydrological properties	Permeability	+
	Inhomogeneity	-
	Thickness of water bearing formation	+
	Resistance of low-permeability layer	-
	Storage coefficient/effective porosity	+
	Unsaturated permeability	+
	Moisture tension	+
	Entrance/radial resistance	+
	Drainage resistance	+
	Fresh/salt	-
	Root zone	+
Initial conditions	Potential	+
	Moisture content/tension	+
Boundary conditions	Potential	-
	Point extraction/infiltration	-
	Moisture content/tension	+
	Potential evapotranspiration	+
	Precipitation	+
	Fresh/salt boundary plane	-
OUTPUT		
Hydrological data	Potential	+
	Flux	+
	Point extraction/infiltration	-
	Moisture content/tension	+
	Actual evapotranspiration	+
	Capillary flux through phreatic surface	+
	Discharge to drains	+
	Water balance	+
Form of output	Print	+
	Plot	-
Sensitivity analysis		+
Testing	Analytical solution	-
	Field measurement	+
	Scale model	-
Computation method	Finite differences	+

Table 14 continued

		MAKKINK/VAN HEEMST
OUTPUT		
Computer	CDC/Cyber	+
Language	Fortran	+
Availability	Conditional	-
	Unconditional	+
Operating manual	System	+
	User	+

Table 15: Models for combined, non-steady, two-dimensional flow in a vertical plane

		UNSAT-2	MM2
INPUT			
Hydrological properties	Permeability	+	+
	Inhomogeneity	+	-
	Anisotropy	+	-
	Thickness of water bearing formation	+	+
	Resistance of low-permeability layer	+	-
	Storage coefficient/effective porosity	+	+
	Unsaturated permeability	+	+
	Moisture tension	+	+
	Entrance/radial resistance	-	-
	Drainage resistance	-	-
	Fresh/salt	-	-
	Root zone	+	-
Initial conditions	Potential	+	+
	Moisture content/tension	+	+
Boundary conditions	Potential	+	+
	Impermeable boundary	+	+
	Flux across boundary	+	+
	Point extraction/infiltration	+	-
	Moisture content/tension	+	-
	Potential evapotranspiration	+	-
	Precipitation	+	+
	Fresh/salt surface	-	-
Network generation		-	-
OUTPUT			
Hydrological data	Potential	+	+
	Flux	+	-
	Point extraction/infiltration	+	-
	Moisture content/tension	+	+
	Actual evapotranspiration	+	-
	Capillary flux through phreatic surface	-	-
	Discharge to drains	-	-
	Stream lines	-	-
	Equipotential lines	-	-
	Travel time	-	-
	Water balance	+	-
	Fresh/salt boundary plane	-	-

Table 15 continued

		UNSAT-2	MM2
OUTPUT			
Form of output	Print	+	+
	Plot	–	–
Sensitivity analysis		+	–
Testing	Analytical solution	–	+
	Field measurement	+	–
	Scale model	–	–
Computation method	Finite differences	–	+
	Finite elements	+	–
Computer	IBM	+	–
	CDC/Cyber	+	–
	DEC	–	+
Language	Fortran	+	+
Availability	Conditional	–	–
	Unconditional	+	+
Operating manual	System	+	–
	User	+	–

Table 16: Models for combined, non-steady, three-dimensional flow

		de LAAT - v.d.AKKER/ (SUM-2/WL/S349-3)
INPUT		
Hydrological properties	Permeability	+
	Inhomogeneity	+
	Anisotropy veen!! peat.	-
	Thickness of water bearing formation	+
	Resistance of low-permeability layer	+
	Storage coefficient/effective porosity	-
	Unsaturated permeability	+
	Moisture tension	+
	Entrance/radial resistance	+
	Drainage resistance	+
	Fresh/salt	-
	Root zone	+
Initial conditions	Potential	+
	Moisture content/tension	-
Boundary conditions	Potential	+
	Impermeable boundary	+
	Flux across boundary	+
	Point extraction/infiltration	+
	Moisture content/tension	-
	Potential evapotranspiration	+
	Precipitation	+
	Fresh/salt boundary plane	-
Network generation		+
OUTPUT		
Hydrological data	→ Potential	+
	Flux	+
	Point extraction/infiltration	+
	Moisture content/tension	+
	Actual evapotranspiration	+
	Capillary flux through phreatic surface	+
	Discharge to drains	+
	Stream lines	-

Table 16 continued

		de LAAT - v.d. AKKER/ (SUM-2/WL/S349-3)
OUTPUT		
	→ Equipotential lines	→ -
	Travel times	-
	Water balance	+
	Fresh/salt boundary plane	-
Form of output	Print	+
	Plot	+
Sensitivity analysis		-
Testing	Analytical solution	-
	Field measurement	+
	Scale model	-
Computation method	Finite differences	-
	Finite elements	+
Computer	IBM	+
Language	Fortran	+
Availability	Conditional	+
	Unconditional	-
Operating manual	System	-
	User	-

5. CONCLUSIONS

1. As regards the survey on the conditions relating to groundwater models, it is evident that these are very divergent, and could not be defined with much exactitude. This is a consequence of the fact that the potential users (groundwater managers) are generally speaking, unacquainted with the possibilities of groundwater models. This is due to the low level of information exchange between model designers and model users. The ad hoc group only knows of a few cases where collaboration between model designers and model users has led to good results.

2. It may be concluded that, generally speaking, a reasonable number of models is available. In view of this the following conclusions may be drawn.

2.1 A large number of the models are rather similar to each other and are probably derived from the same basic model.

2.2 In general the models are poorly documented. Consequently it is often difficult and time-consuming for the users to work with them.

2.3 The testing of the models with field data has only been done on an outline basis, but it is only this testing which can give some impression of the reliability of the models.

2.4 In many cases, the sensitivity of the model results to changes in parameters is not investigated.

2.5 The number of truly three-dimensional models is small. Most of the three-dimensional models cited in this survey are pseudo-three-dimensional, i.e. they relate to a number of water-bearing formations in which two-dimensional horizontal flow occurs, separated by semi-permeable layers in which only vertical flow takes place.

2.6 The absence of inverse models in The Netherlands is striking, i.e. models allowing the soil constants to be calculated using measured groundwater levels and boundary conditions.

2.7 The number of models which allow many-fluid problems (e.g. fresh/salt) to be calculated is small, while simple methods are generally used.

2.8 If the relation between ground- and surface water is already incorporated in a model, it has often been done in an arbitrary way, generally because insufficient discharge data are available.

2.9 Although the deep soil layers are generally not isotropic, anisotropy is only incorporated in a few models.

2.10 In a number of models it is possible to have an impermeable boundary as a boundary condition, but not a fixed flux across the boundary. This is despite the fact that both cases are mathematically identical.

LITERATURE

VAN DEN AKKER, C., 1975 -
Toelichting bij het rekenprogramma FLOP-1.(explanatory note to the computer programma FLOP-1) RID Communication 75-3.

BERKHOFF, J.C.W.,
Drie-dimensionale grondwaterstroming (potentiaalstroming).(Three-dimensional groundwater flow (potential flow)). Internal report W 316 WL.- Delft.

COMMISSIE BESTUDERING WATERHUISHOUDING GELDERLAND, 1976 -
Modelonderzoek 1971 - 1974 ten behoeve van de waterhuishouding in Gelderland.(Model investigation 1971-1974 for the purpose of water management in Gelderland). Working group report 1. (internal report).

CRANK, J. & P. NICHOLSON, 1974 -
A practical method for numerical evaluation of solutions of partial differential equations of heat conduction type.
Proc. Comb. Phil. Soc. 43, pp.50-67.

DOUGLAS Jr., J. & B.F. JONES, 1963 -
On predictor-corrector methods for non-linear parabolic differential equations.
Journ. SIAM, 11, pp.195-204.

FEDDES, R.A., E. BRESLER & S.P. NEUMAN, 1974 -
Field tests of a modified numerical model for water uptake by root systems.
Water Res. Res. 10(6), pp.1199-1206.

FINLAYSEN, B.A., 1972 -
The method of weighted residuals and variational principles.
New.York,Academic Press.

FORSYTHE, G.E. & W.R. WASON, 1960 -
Finite difference methods for partial differential equations.
New York, John Wiley and Sons.

FREEZE, R.A., 1971 -
Three dimensional, transient, saturated-unsaturated flow in a ground water basin.
Water Res. Res. 7(2), pp.347-366.

HAITJEMA, H.M., 1977 -
Numerical applications of vortices to multiple fluid flow in porous media.
Delft Progress Report 2 (1977), pp.237-248.

HORNBERGER, G.M., I. REMSON & A.A. FUNGAROLI, 1969 -
Numerical studies of a composite soil-moisture ground water system.
Water Res. Res. 5(4), pp.797-802.

DE JOSSELIN DE JONG, G., 1977 -
Review of vortex theory for multiple fluid flow.
Delft Progress Report 2 (1977), pp.225-236.

KREYSZIG, E., 1972 -
Advanced engineering mathematics.
New York, John Wiley and Sons.

DE LAAT, P.J.M., C. VAN DEN AKKER & TH.J. VAN DE NES, 1975 -
Consequences of ground water extraction on evapotranspiration and saturated-unsaturated flow.
Proc. Bratislava symposium, IAHS-publ. no. 115, pp.67-76.

DE LAAT, P.J.M., 1976 -
A pseudo steady-state solution of water movement in the unsaturated zone of the soil.
Journ.Hydrol. 30, pp.19-27.

LOTHIN, M., 1958 -
The numerical integration of heat conduction equations.
Journ. Math.Phys. 37, pp.178-187.

NEUMAN, S.P., 1973 -
Saturated-unsaturated seepage by finite elements.
Proc. of Hydr. Div. 99 (HY12), pp.2233-2250.

NORRIE, D.H. & G. DE VRIES, 1973 -
The finite element method.
New York, Academic Press.

PEACEMAN, D.W. & H.H. RACHFORD, 1955 -
The numerical solution of parabolic and elliptic differential equations.
Journ. SIAM, 3, pp.28-41.

REMSON, I., G.M. HORNBERGER & F.J. MOLZ, 1971 -
Numerical methods in subsurface hydrology.
New York, Interscience.

RUBIN, J., 1968 -
Theoretical analysis of two dimensional transient flow of water in unsaturated and partly unsaturated soils.
Soil Sci. Soc. Amer.Proc. 32(5), pp.607-615.

SMITH, G.D., 1965 -
Numerical solutions of partial differential equations.
New York, Oxford Univ. Press.

TAYLOR, G.S. & J.N. LUTHIN, 1969 -
Computer methods transient analysis of water table aquifers.
Water Res.Res. 5(1), pp.144-152.

VAN DER VEER, P. 1976 -
Calculation method for two dimensional ground water flow.
Delft Progress Report 2 (1976), pp.35-49

VERMA, R.D. & W. BRUTSAERT, 1970 -
Unconfined aquifer seepage by capillary flow theory.
Journ. Hydr. Div. 96(HY6), pp.1331-1344.

ZIENKIEVICZ, O.C., 1971 -
The finite element method in engineering science.
London, Mc. Graw Hill.

APPENDIX 1

INSTITUTIONS SENT QUESTIONNAIRES

- Technische Hogeschool (TH) (Technical University), Delft.
- Landbouwhogeschool (LH) (Agricultural University), Wageningen.
- Vrije Universiteit (Free University), Amsterdam.
- Laboratorium voor Grondmechanica (Soil Mechanics Laboratory), Delft.
- Waterloopkundig Laboratorium (Delft Hydraulics Laboratory Delft - and Department 'De Voorst', Emmeloord.
- Instituut voor Cultuurtechniek en Waterhuishouding (ICW) (Institute for Land and Water-Management), Wageningen.
- Rijkswaterstaat (Government Water Dept.)
- Provinciale Waterstaatsdiensten (Provincial Water Boards)
- Rijksinstituut voor Drinkwatervoorziening (National Institute for Water Supply), Voorburg.
- Vereninging van Exploitanten van Waterleidingbedrijven in Nederland (Netherlands Water Works Association), Rijswijk.
- Technisch Secretariaat Commissie Condwet Waterleidingbedrijven (Technical Secretariat of the Commission of Groundwater Law on Public Water Supply) Utrecht.
- Institute for Land Reclamation and Improvement (ILRI), Wageningen.
- International Institute for Hydraulic and Environmental Engineering, Delft.
- Ingenieurbureaus (Consulting Engineers).
- Keuringsinstituut voor Waterleidingartikelen (Netherlands Water Works Testing and Research Institute), Rijswijk.
- Unie van Waterschappen (Union of Water Boards), The Hague
- Staätsbosbeheer (State Forestry Administration), Utrecht.
- Rijksdienst voor de IJsselmeerpolders (RIJP) (IJsselmeer-Polders Development Authority), Lelystad.
- Dienst Grondwaterwerkenning TNO (TNO Groundwater Survey) Delft.
- Stichting voor Bodemkartering (Soil Survey Institute), Wageningen.
- Gemeentelijke Technische Diensten (Local Public Works Departments)
- Rijks Geologische Dienst (Government Geological Survey), Haarlem.
- Cultuurtechnische Dienst(Government Service for Land and Water Use), Utrecht.

APPENDIX 2

QUESTIONNAIRE on requirements relating to groundwater mode

1\. Why do you think you need a model?

2\. For what scale must the model be suitable?

3\. What is your management/control field, or study/research field?

4\. In what time period do you expect an answer?

5\. What does the model have to simulate (output needed)?

6.1 What degree of detail is required in relation to the output data of the model in terms of place and time?

6.2 What budget is available for using groundwater models?

7\. Have you problems in obtaining data, and if so, please specify.

8.1 Which models do you use and what is your experience with them?

8.2 For which part of your problem do you use these models?

9.1 Is the task within the institution itself or do you subcontract it; what is your experience?

9.2 What is your plan of actions in the future?

10\. What do your own computing facilities consist of?

11\. What other questions would you like to see answered?

APPENDIX 3

QUESTIONNAIRE on the availability of numerical groundwater models

1. Which digital models do you have in use?
2. What does the model simulate?
3. What are the theoretical backgrounds (in brief)?
4. What input data are necessary, what preliminary operations are needed and can the computer be employed for these if necessary?
5. What does the model compute, what is the field of application and what are the limitations?
6. What is the output of the model and what form does it take?
7. What detailing in terms of place and time do you use and what is desirable and/or necessary for practical applications?
8. Do you apply sensitivity analysis and, if so, for which input data and what are the results?
9. Has the model been tested on measurements and/or analytical solutions and what is the reliability?
10. For which computer is the model suitable and in which language is it written?
11. How expensive is the model in operation in relation to terms of place and time?
12. Is the model generally available and if so, where and under what conditions?
13. By whom and for whom is the model used?
14. Is documentation available on the model and if so, is this documentation directed to the user or the system? Can the model only be used with the aid of this documentation?
    From whom can detailed information be obtained?
15. What analog models do you have in use and what is the experience with them?
16. What analytical solutions do you use and what is the experience with them?
17. What qualitative models do you use and what is the experience with them?
18. Can you suggest other institutions or people to whom questionnaires should be sent?

APPENDIX 4

BRIEF DESCRIPTION OF EXISTING GROUNDWATER MODELS

Saturated, steady, 2 dimensional horizontal models (see Table 5)

LM 1	Flow in a horizontal plane. A Verruyt, Civil Engineering Department, TH - Delft P.O. Box 5048, Delft.
LM 4 IWA 124	As LM 1, buth with extraction by wells. A. Verruyt, Civil Engineering Department, TH - Delft, P.O. Box 5048, Delft. A. Bot, IWACO, P.O. Box 183, Rotterdam.
IWA 139	Transit-time and streamline calculations in the case of confined or semi-confined phreatic water for extraction at one or more wells. A. Bot, IWACO, P.O. Box 183, Rotterdam.
THEO	Simulation of the potential field for flow in a water-bearing layer with fully confined water, and with extraction and fixed charging per element. Th. Olsthoorn, KIWA NV, Sir Winston Churchill-laan 273, P.O. Box 70, Rijswijk (ZH).
FLOP-1	Calculation of streamlines and travel time for flow in a water-bearing layer with fully confined water. C. van den Akker, GWL, Condensatorweg 54, P.O.Box 8169, Amsterdam-Sloterdijk. W. Fillekes, RID, P.O. Box 150, Leidschendam.
FLOP-2	As FLOP-1, but in a water-bearing layer with partially confined water. C. van den Akker, GWL, Condensatorweg 54, P.O. Box 8169, Amsterdam-Sloterdijk. W. Fillekes, RID, P.O. Box 150, Leidschendam.
IWA 132	Flow in a 1-layer thick formation with precipitation, extraction and infiltration. A. Bot, IWACO, P.O. Box 183, Rotterdam.
ICW 1	Calculation of seepage/leakage in an area. J.G. Wesseling, c/o ICW, P.O. Box 35, Wageningen.
ICW 3	Calculation of the potential field in an aquifer with extraction/infiltration and precipitation/evaporation. J.G. Wesseling, c/o ICW, P.O. Box 35, Wageningen.

Some of the abbreviations for institutions are given in Appendix 1.

Saturated, steady, 2-dimensional vertical models (see Table 6)

IWA 153	Change in the fresh-salt boundary plane and pressure head for extraction of salt water in a 1-, 2- or 3-layer system. A. Bot, IWACO, P.O. Box 183, Rotterdam.
RWR 01 RWR 06	Flow into a drain/ditch in a 2-layer system. R.W.R. Koopmans/G.J.R. Soer, Agrohydrological Department, LH - Wageningen, Nieuwe Kanaal 11, Wageningen.
WIDMOS	Transformation of a radial flow into a drain with filter into a simpler flow to determine the influence of perforation and filter on the entry resistance of drain tubes. G.J.A. Nieuwenhuis, ICW, P.O. Box 35, Wageningen.
ICW 2	Flow through a straight and sloping dam with a free groundwater table. J.G. Wesseling, c/o ICW, P.O. Box 35, Wageningen.
AGS 03	Flow through a straight dam with a free groundwater table. G.J.R. Soer, Agrohydrological Department, LH - Wageningen, Nieuwe Kanaal 11, Wageningen.

Saturated, steady, 3-dimensional models (see Table 7)

STATRECT-2	Calculation of pressure heads and fluxes in a 1- or 2-layer system with extraction. W. Fillekes, RID, P.O. Box 150, Leidschendam.
TRIST	Flow in a 2-layer system with extraction, infiltration and seepage A. Leijnse, RID, P.O. Box 150, Leidschendam.
IWA 135	As IWA 132 (table 5) but in a 2-layer system. A. Bot, IWACO, P.O. Box 183, Rotterdam.
IWA 136	As IWA 132 (table 5) but in a 3-layer system. A. Bot, IWACO, P.O. Box 183, Rotterdam.
v.d. Akker ALMERE	Flow in a 2-layer system with extraction. C.v.d. Akker, GWL, Condensatorweg 54,P.O.Box 8169,Amsterdam-Sloterdijk E. Schultz, RIJP, Smedinghuis,P.O. Box 600, Lelystad.
WL/W 316-1	Calculation of groundwater flow beneath a damming construction in open water. A.P.M. Broks, Hydraulics Laboratory, Department "de Voorst", P.O. Box 152, Emmeloord.

Saturated non-steady, 2-dimensional horizontal models (see Table 8)

MOTGRO	Flow of one or more fluids in an area of arbitrary shape and characteristics, with extraction. P. v.d. Veer Rijkswaterstaat, Data Processing Division. Nijverheidsstraat 1, Rijswijk (ZH).
ILRI 1	Prediction of groundwater depths in relation to recharge and extraction. N.A. de Ridder/J. Boonstra, ILRI, P.O. Box 45 Wageningen.
FRONT	As FLOP-1 (table 5), but with storage variations. C. v.d. Akker, GWL, Condensatorweg 54, Postbus 8169, Amsterdam-Sloterdijk. W. Fillekes, RID, P.O. Box 150, Leidschendam.
HEIDMY -1	Prediction of groundwater depths in relation to extraction and infiltration, with parameters for drainage into rivers. D. Pette, Adviesbureau Arnhem B.V, P.O. Box 264, Arnhem
WL/S 135-1	Groundwater flow in a phreatic surface. A.P.M. Broks, Hydraulics Laboratory "de Voorst", P.O. Box 152, Emmeloord.
TYSON	As ILRI 1, but with relation to surface water. G.J.R. Soer, Agrohydrological Department, LH - Wageningen, Nieuwe Kanaal 11, Wageningen.

Saturated Non-steady, 2-dimensional vertical models (Table 9)

MOTRGRO	See under MOTGRO "horizontal" (table 8)
IWA 154	As IWA 153, but with changes in storage extraction variation. A. Bot, IWACO, P.O. Box 183, Rotterdam.
LM 6	Calculation of free groundwater surface in a straight dam. A. Verruyt, Civil Engineering Department, TH - Delft. P.O. Box 5043, Delft. A. Bot, IWACO, P.O. Box 183, Rotterdam.
MUFLO 3/4	Calculations of boundary planes between several fluids. H.M. Haitjema, Civil Engineering Department, TH - Delft. P.O. Box 5048, Delft.

RWR 03	Flow towards a drain in a 2-layer system.
RWR 05	Flow through a homogeneous, isotropic dam.
RWR 08	Flow through a drain on an incline.
RWR 10	Flow towards a partially penetrating well.
RWR 12	Flow towards a drain (ADI method).
RWR 13	As RWR 03, but towards a drainage trench with varying permeability.
	R.W.R. Koopmans/G.J.R. Soer, Agrohydrological Department, LH - Wageningen, Nieuwe Kanaal 11, Wageningen.
WL/S 135-2	Calculation of groundwater flow through a straight dam with a free surface. A.P.M. Broks, Hydraulics Laboratory, Department "de Voorst", P.O. Box 152, Emmeloord.
AGS 01 AGS 02	As AGS 03, but non steady. G.J.R. Soer, Agrohydrological Department, LH- Wageningen, Nieuwe Kanaal 11, Wageningen.

Saturated non-steady, 3-dimensional models (see Table 10)

SEEP	Non-steady, 3-dimensional flow through a (semi) saturated, rigid, inhomogeneous, anisotropic medium. F. Barends, Soil Mechanics Laboratory, Stieltjesweg 2, P.O. Box 69, Delft.
TRANSRECT-2	As STATRECT - 2 (table 8), but with storage changes. W. Fillekes, RID, P.O. Box 150, Leidschendam.
v. BAKEL	Calculation of potential distribution for flow towards wells, with precipitation. P.J.T. van Bakel, ICW, P.O. Box 35, Wageningen.

Unsaturated, steady, 1-dimensional vertical models (see Table 11)

CAP.OPST.	Calculations of capillary rise from the groundwater table in layered profiles. K. Rijniersce, RIJP, Smedinghuis, P.O. Box 600, Lelystad.
WL/S 349 -1	Calculation of steady water flow in the unsaturated zone. A.P.M. Broks, Hydraulic Laboratory, Department "de Voorst" P.O. Box 152, Emmeloord.

Unsaturated, non-steady 1-dimensional vertical models (see Table 12)

HEIDONS	Calcuations of moisture shortages from soil hydrological and meteorological data. H.J. Vinkers, Adviesbureau Arnhem B.V., P.O. Box 264, Arnhem.
FLOW	Flow in a homogeneous soil with precipitation/ evaporation and discharge via drainage. G.P. Wind, ICW, P.O. Box 35, Wageningen.
FEDDES	Flow in a homogeneous soil with water removal via roots for a constant groundwater level with precipitation and evapotranspiration. R.A. Feddes, ICW, P.O. Box 35, Wageningen.
SOILWAT	Flow in layered soil profile with water extraction by roots with varying groundwater level, with precipitation and evapotranspiration. R.A. Feddes, ICW, P.O. Box 35, Wageningen.
v. KEULEN	Rootwater extraction from homogeneous soil, without groundwater level, with precipitation and evapotranspiration. H. van Keulen, Theoretical Cultivation Science Department, LH - Wageningen, De Dreijen 2, Wageningen.
WL/S 349-2	Calculation of non-steady groundwater flow in the unsaturated zone. A.P.M. Broks, Hydraulics Laboratory,Department "De Voorst", PO Box 152, Emmeloord.

Combined, steady, 2-dimensional vertical models (see Table 13)

BOELS	Sub-infiltration from streams into deeply sited groundwater. D. Boels, ICW, P.O. Box 35, Wageningen.

Combined, non-steady, 1-dimensional vertical models (see Table 14)

MAKKINK/ v. HEEMST	Water balance in a saturated-unsatirated medium, with precipitation, evapotranspiration and drainage. H.D.J. v. Heemst, CABO, Bornsesteeg 65, P.O. Box 14, Wageningen.

Combined, non-steady, 2-dimensional models (see table 15)

UNSAT 2	Flow in saturated-unsaturated medium with water extraction by roots, precipitation, evapotranspiration, groundwater extraction and infiltration/drainage. R.A. Feddes, ICW, P.O. Box 35, Wageningen.
MM2	Flow in a saturated-unsaturated medium limited by ditches and precipitation. Y. Matsuura, c/o G.J.R. Soer, Agrohydrology Department, LH- Wageningen., Nieuwe Kanaal 11, Wageningen.

Combined, non-steady, 3-dimensional models (see table 16)

De LAAT-v.d. AKKER SUM 2 WL/S 349 -3	Flow in a saturated-unsaturated medium in relation to precipitation, evapotranspiration, groundwater extraction and sub-infiltration drainage P.J.M. de Laat, IHE, Oude Delft 95, Delft. C.v.d, Akker, GWL, Condensatorweg 54, P.O. Box 8169, Amsterdam- Sloterdijk. H.A.J. v. Lanen, RID, P.O. Box 150, Leidschendam. A.P.M. Broks, Hydraulic Laboratory, Department "de Voorst", P.O. Box 152, Emmeloord.