# THE USE OF GEOHYDROLOGY IN SOLVING WATER MANAGEMENT PROBLEMS IN AGRICULTURE

J. WESSELING[1]) and H.J. COLENBRANDER[2])

## ABSTRACT

For the study of water management problems in agriculture often the same hydrologic parameters and calculation techniques are applicable as for civil engineering studies (e.g. foundations) and drinkwater supply studies (e.g. extraction and recharge of water). Therefore, arbitrary subdivision of hydrology as agro-hydrology, geohydrology etc. does not always make much sense.

In this paper the use of some hydrologic calculation techniques in solving water management problems in agriculture is elucidated.

## 1. INTRODUCTION

Since the beginning of the 20th century proper water management is considered as one of the main conditions for a high level agriculture in humid climates, such as prevailing in the Netherlands. During this time most of the country's drainage systems have been improved considerably or even renewed completely.

During the past two decades accelerated mechanization in agriculture has stressed the importance of water control. Heavy machinery requires high bearing strengths and therefore dry soils. High investment costs for this machinery, lack of labour and a relatively short growing season cause farmers to manage their soils in a rather short period in spring. Wet soil conditions do not only cause deterioration of soil structure but require extra labour and machinery costs. Moreover a delay in sowing time may give considerable yield depressions.

The article gives a brief review of the hydrological conditions in the Netherlands. Some examples will be given of the use of geohydrology in solving water management problems in agriculture.

[1]) Institute for Land and Water Management Research, Wageningen.
[2]) Provincial Water Board of Gelderland, Arnhem.

## 2. HYDROLOGICAL CONDITIONS IN THE NETHERLANDS

Rainfall is nearly evenly distributed over the year. Evapotranspiration amounts only a few millimeters per month in winter time whereas it is about 120 mm per month in June and July. Generally spoken there is an excess in winter periods and a shortage in the summer. During the latter period part of the water requirement of the plants is provided by soil moisture.

In the major part of the country groundwater is within the reach of plant roots most of the year. From the standpoint of water management the Netherlands can be divided into two nearly equal parts:

a. the flat western and northern area with mainly peat and clay soils and a soil surface around or below sea-level drained by pumping.
b. the more undulating eastern and southern sandy region with higher soil surface level, drained by gravity.

In the first part a given water level is maintained throughout the year in order to satisfy water requirements of crops and to prevent subsidence in case of peat soils. In the latter part water supply in summer is usually insufficient and here water conservation plays an important role.

In the western polder region groundwater is often saline or brackish whereas in the eastern part it is fresh. Therefore pumping of groundwater for domestic and industrial purposes may interfere with agricultural water management in the latter area.

In both areas water management is realized by the drainage system. In the low part the occurrence of seepage (positive or negative) determines to a large extent the capacity of the system, including that of the pumping plants. Moreover seepage determines the quality of the drainage water mainly due to its saline nature. Since open water is frequently used for irrigation of horticultural crops, water quality is an important aspect of water management. In the higher part the main point is regulation of the water level in the drainage systems and consequently of the groundwater table in order to prevent drought damage during the summer. In other words the depth of the water table during the course of the year is important.

It is evident that groundwater flow plays an important role in agricultural water control. Geohydrology in the form of interpretation of deep borings and application of physical-mathematical solutions of flow problems are of great help in solving water management problems. These geohydrologic methods, used much earlier in civil engineering (foundations, water supply), were introduced in agriculture to this country only some 35 years ago by the late Dr. Hooghoudt of the Soil Fertility Institute at Groningen (e.g. H o o g h o u d t, 1935).

## 3. HYDROLOGICAL ANALYSIS

The hydrological analysis of a given area implies in fact determination of the water balance for any given time. This means that one tries to get as good an insight as possible what factors are influencing the water movement within the area. If these factors are known one is able to forecast what effect given changes in the area will have on the water balance.

A complete description of all effects will seldom, if ever, be possible, due to errors and shortcomings in the applied methods and the often very complicated interrelation between the various factors involved. Therefore one is often obliged to use different methods simultaneously in order to attain a certain completeness.

Applying geohydrological methods, one should first try to characterize the area in terms of geohydrological parameters. These parameters can be substituted in formulas describing the flow in the area for certain boundary conditions. For this purpose the boundary conditions of the flow problems must be the same as those for which the formulas have been derived. In other words the schematization of the flow must be in accordance with natural conditions. Deviations from these conditions often give larger errors than inaccuracies in the hydrological parameters.

The method to be applied in finding geohydrological characteristics will depend on type and amount of available data on the one hand and on existing flow conditions in the area on the other hand. Sometimes prevailing conditions allow a direct analysis of piezometric data, whereas in other cases special conditions must be created.

### 3.1 *Investigations in the lower part*

First a series of examples of geohydrological investigations that have been carried out during the past years in the low lying western part of the country, will be discussed. Most of the problems in this area pertain to the so-called Dutch profile, i.e. a water bearing formation or aquifer covered by a less permeable peat or clay layer. Water movement in this profile is mainly horizontal through the aquifer and vertical through the covering layer.

Groundwater flow is determined to a large extent by the hydrological conditions in these areas. For estimating net subsurface flow, two ways can be followed namely:

a. the indirect method, in which transmissivity of the underlying aquifer and the vertical resistance of the covering layer are determined;
b. direct methods in which data on piezometric head or discharge data from pumping plants are used.

For the indirect method several tools are available. Geohydrological factors can be determined by using:

a. Disturbed samples of geological borings.

b. Field pumping tests.
c. Undisturbed soil samples taken during borings.
d. Analysis of data on piezometric head with the aid of flow equations.

For soil layers with little or without silt a correlation between hydraulic conductivity and grain size distribution may be expected. For Dutch conditions (H o o g h o u d t, 1935; v a n D u i n, 1956; d e R i d d e r and W i t, 1965), it was found that:

$$kU^2 = \text{constant} \tag{1}$$

where k represents hydraulic conductivity and U is the specific surface of the soil, the latter being dependent of grain size. The value of the constant ranges between 25 000 and 75 000 dependent on average grain size of the soil.

The execution of field pumping tests is a well-known method to obtain soil constants. Recently K r u s e m a n and d e R i d d e r (1970) have given a complete review of methods for analyzing pumping test data. For methods especially used in the Netherlands the reader is referred to the TNO publication on this subject (Anonymous, 1966).

Undisturbed smaples need special equipment for coring and measuring. The apparatus used by the Institute for Land and Water Management Research have been described in detail by W i t (1960, 1962, 1967). Values for both horizontal and vertical hydraulic conductivity can be obtained.

For the analysis of piezometric data a known solution for the flow problem must be available, in other words the field conditions must fit the boundary conditions for which the theoretical solution has been derived. A typical example is the piezometric head in a semi-confined aquifer bounded by a river (fig. 1). For the piezometric head in any row orthogonal to the river M a z u r e (1936) derived the formula:

$$\phi_x = \phi_o e^{-x/\lambda} \tag{2}$$

where $\phi_x$ is the piezometric level in the aquifer at a distance x from the river. Further $\lambda = \sqrt{kDc}$ contains the hydrological constants of the semi-confined aquifer.

C o l e n b r a n d e r (1961) measured heads in some rows of piezometers orthogonal to the river. Some of the obtained results are given in fig. 2. For both rows the data fit eq. 2 very well. Since the heads have been plotted on a logarithmic scale, straight lines must be obtained. From the slope of these lines it can be found that $\lambda$ = 1400 meters.

Another possibility of getting hydrological constants is the application of the theory of Steggewentz. For a full description of this theory the reader is referred to the orginal contribution (S t e g g e w e n t z, 1933) and to B o s c h (1951), W e s s e l i n g (1958) and W e s s e l i n g (1960).

When the river's water level is subject to tides, it can be represented by a series of sinusoides, hence:

$$\phi_o(t) = \bar{\phi} + A_o \sin nt \tag{3}$$

where $\bar{\phi}$ is the average level, $A_o$ the amplitude and $n = \frac{2\pi}{T}$ represents the frequency of the movement. In this case the piezometric head of the groundwater in the aquifer can be represented by:

$$\phi(x,t) = \bar{\phi} + A_o e^{-ax} \sin(nt + bx) \tag{4}$$

taking into account the elasticity of the aquifer and the water within it. The relation between the damping a the phase shift b and the hydrological parameters according to B o s c h (1951) are:

$$a^2 - b^2 = \frac{1}{kDc} \quad (5a) \qquad 2ab = \frac{Sn}{kD} \quad (5b)$$

where S represents the stoarage coefficien ($\approx$ effective porosity) of the aquifer.

Fig. 3 gives the results of some measurement in

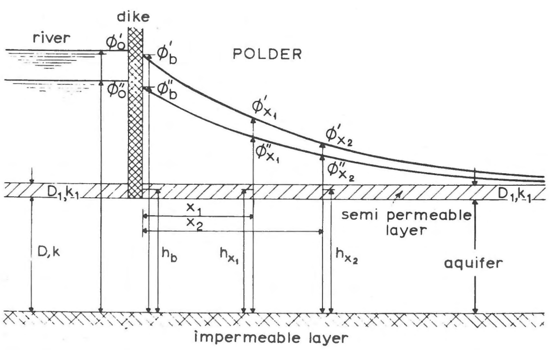


Fig. 1
Schematic hydrological profile for flow from a river into a groundwater aquifer (Colenbrander, 1961a).

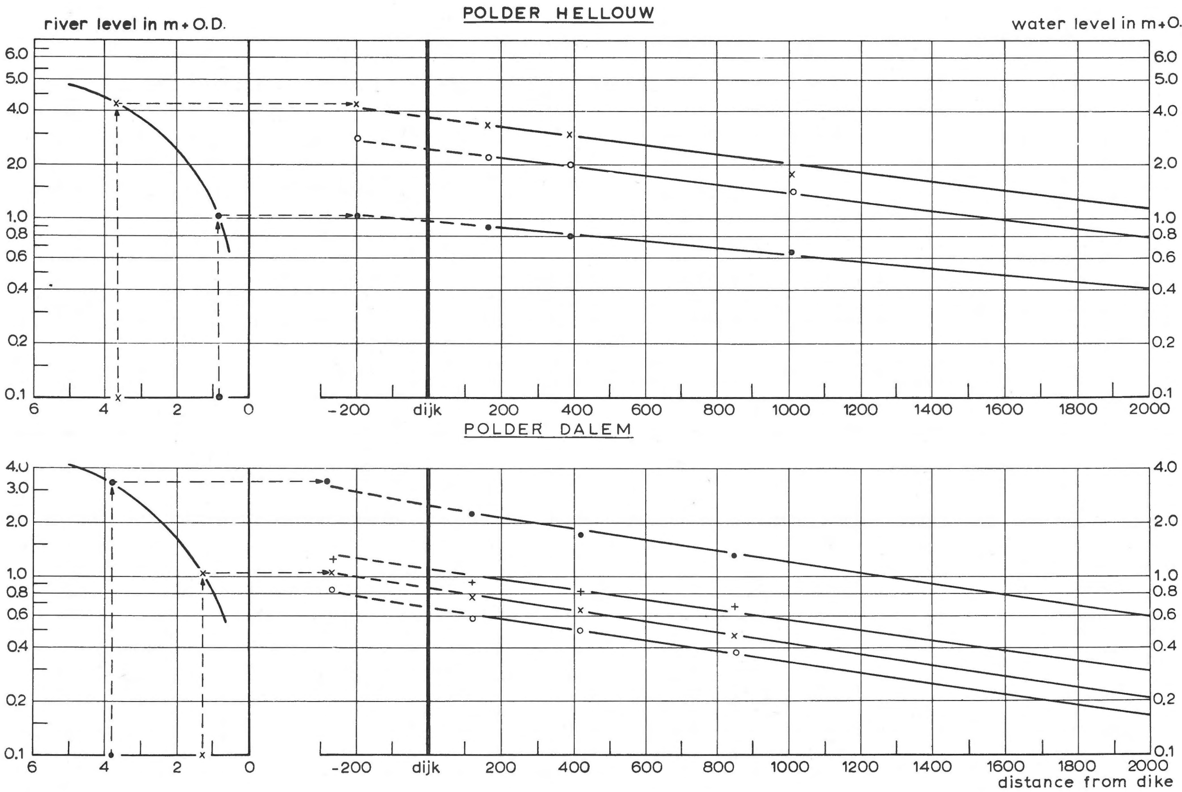


Fig. 2
Some observations of piezometric levels on rows orthogonal to the river Waal (Colenbrander, 1961a).

piezometers close to a river. Both damping and phase shift are clearly shown.

From eqs. 3 and 4 a relationship for the amplitude of the tidal movement may be derived:

$$\ln \frac{A_x}{A_o} = -ax \qquad (6)$$

where $A_x$ is the amplitude at any distance x from the river and $A_o$ is the amplitude in the river water. By plotting $\ln \frac{A_x}{A_o}$ against x one finds a straight line having a slope equal to -a. Fig. 4 gives some examples of such an analysis.

Plotting the phase shift against the distance also a straight line will be obtained as shown in fig. 4. The slope of the latter line is equal to b. Using the average values of a and b found from fig. 4, one obtains $\lambda$ = 530 m and $\frac{S}{kD} = 0.60 \times 10^{-6}$ days/m$^2$. It may be noted that d e R i d d e r (1961) found from pumping tests in this area kD-values between 2170 and 3030 m$^2$/day, c-values between 560 and 210 days and $\lambda$-values between 1100 and 800 meters.

C o l e n b r a n d e r (1961) used the water balance to determine indirectly seepage amounts for some

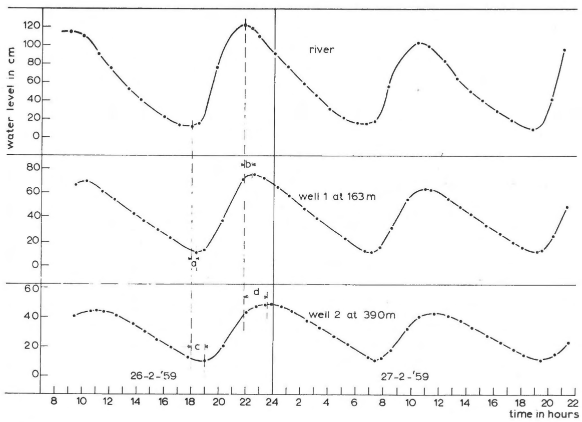


Fig. 3
Levels in the river Waal on two observation wells (Wesseling and Colenbrander, 1961).

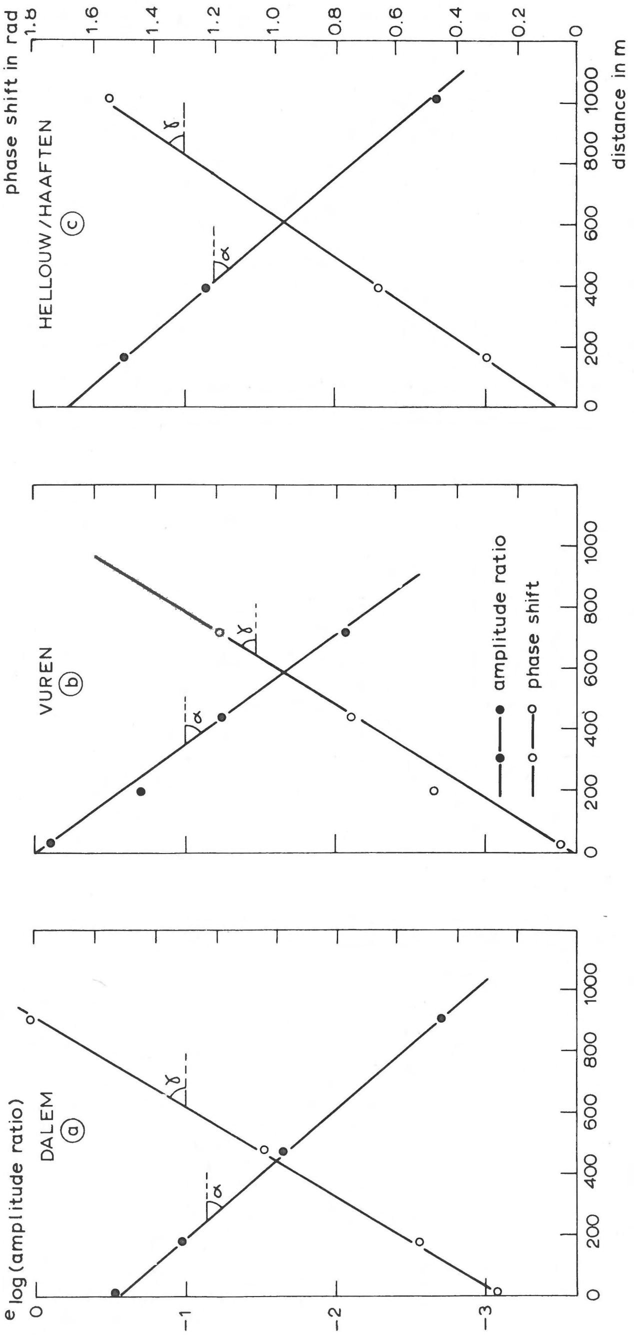


Fig. 4
Amplitudes and phase shifts as a function of the distance from the river for three piezometric wells (Wesseling and Colenbrander, 1961).

polders along the river Waal. By using discharge data of pumping plants he was able to find the relation between influent seepage in the polder and the stage of the river (fig. 5).

During river regulation works in the eastern part of the Province of Gelderland, a diversion channel was constructed through the river valley. Due to the low elevation of the soil surface in the valley, the water level of this canal was above soil surface. In order to determine the seepage losses from this canal the Provincial Water Board in Arnhem placed some rows of piezometers perpendicular to the canal and raised the water level from 6.42 meters to 8.02 meters + O.D. for about 10 days. Piezometric data were collecting during this period. Fig. 6 gives the results of the observations in one row of piezometers. The present authors applied the theory of Edelman to these data. E d e l m a n (1947) derived for a sudden change of the open water level for the change of the groundwater in the adjoining soil:

$$\phi\ (x,t) = \phi_o \ \mathrm{erfc}\ (u) \qquad (7)$$

where erfc stands for the complemental error function:

$$\mathrm{erfc}(u) = 1 - \frac{2}{\sqrt{\pi}} \int_0^u e^{-\epsilon^2}\, d\epsilon \qquad (8)$$

and $u = \frac{x}{2\sqrt{T}}$, $T = \frac{kDt}{p}$

with p representing the effective porosity or drainable pore space of the soil and t the time.

The flow through any cross-sectional area of unit width at distance x from the channel is given by:

$$q = \frac{\phi_o}{\sqrt{\pi}}\ t^{-1/2} e^{-u^2} \sqrt{kD.p} \qquad (9)$$

and since for $x = 0$, $e^{-u^2} = 0$ the flow out of the channel towards one side is given by:

$$q_o = \sqrt{kDp}\,\frac{\phi_o}{\sqrt{\pi}}\ t^{-1/2} \qquad (10)$$

Since erfc (u) can be found in published tables a procedure similar to that used for the analysis of pumping test data can be applied (K r u s e m a n and d e R i d d e r, 1970; d e G l e e, 1951).

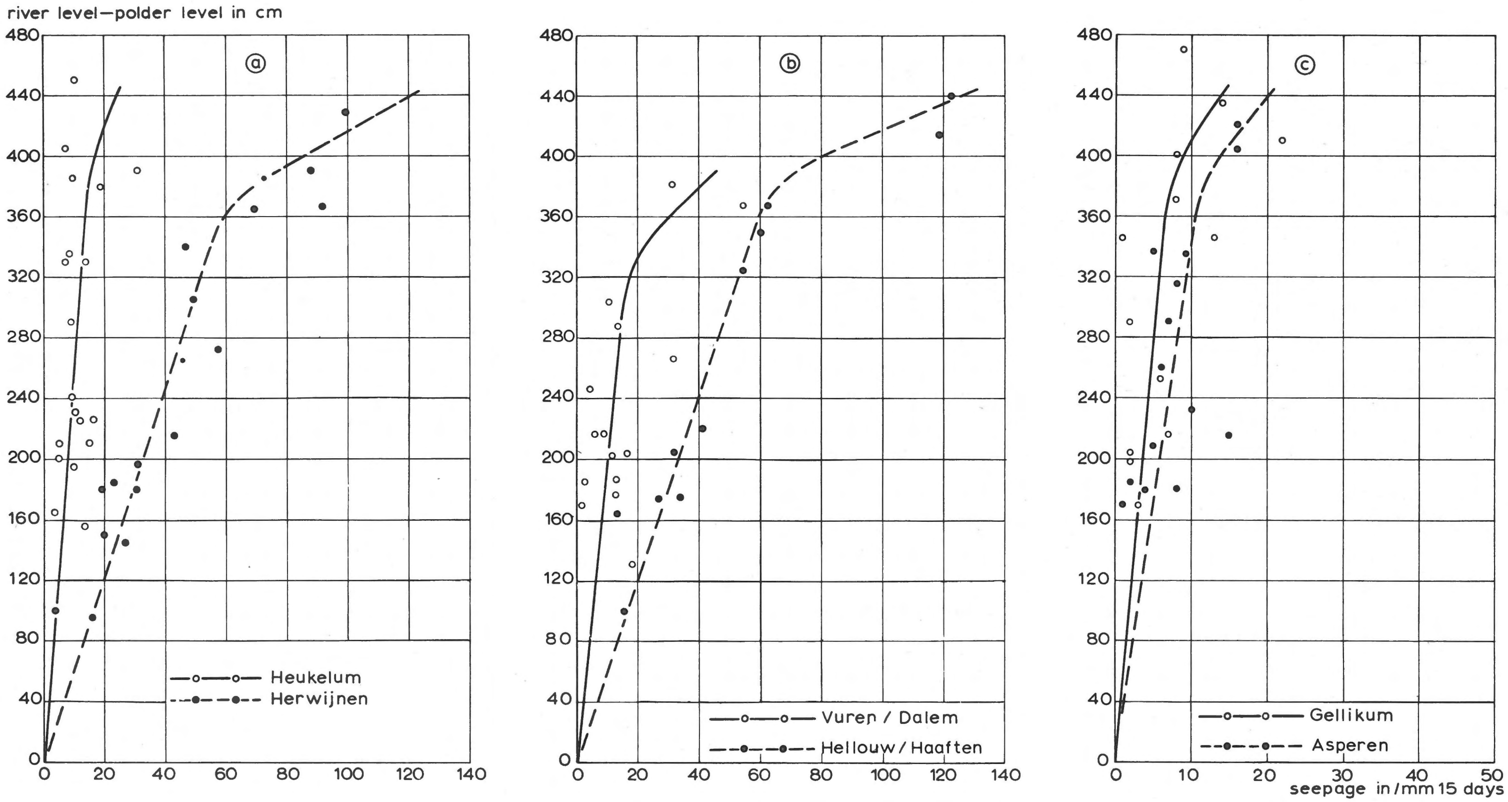


Fig. 5
The relation between the difference between river stage and polder level on the one hand and influent seepage for some polders in the Tielerwaard-West on the other hand (Colenbrander, 1961b).

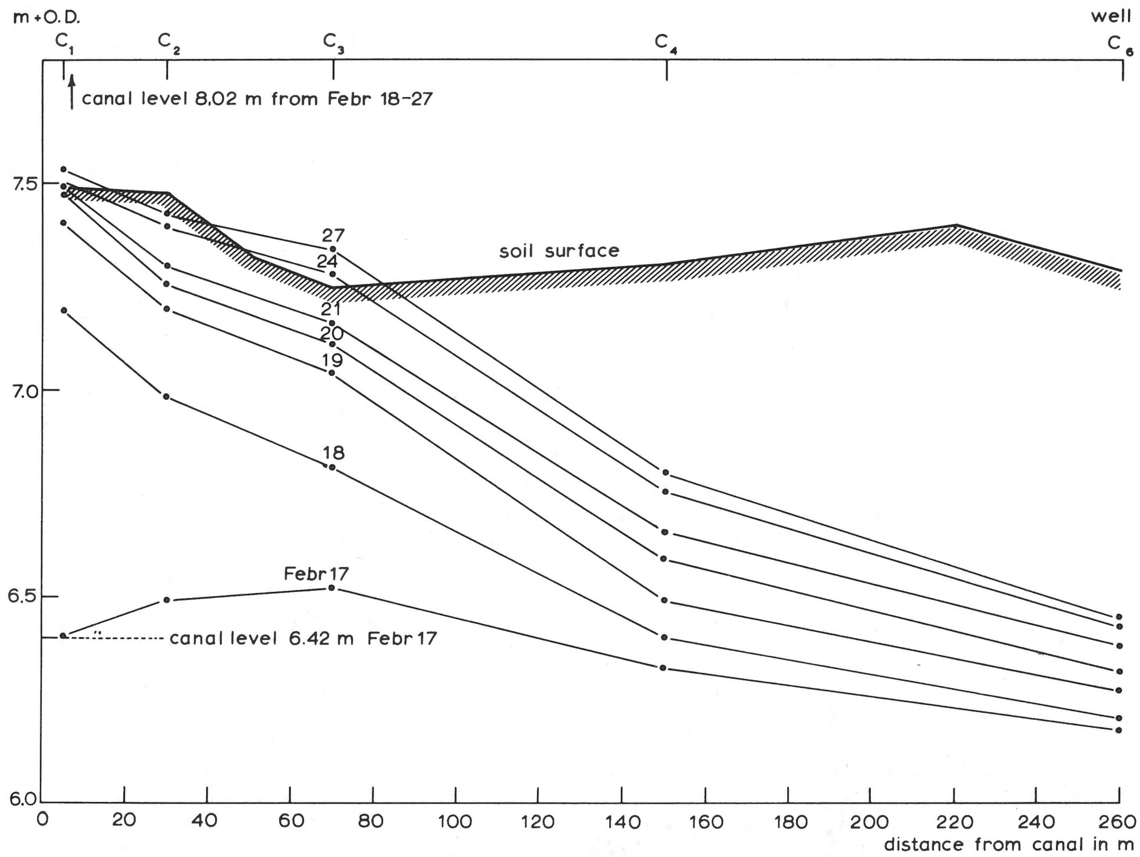


Fig. 6
Observations of piezometric wells along a canal at various times after the canal level had been raised.

For this purpose values for $\phi/\phi_o$ are computed and plotted on log-log paper against $\frac{x}{\sqrt{t}}$. Next a so-called type curve or master chart is constructed for values of erfc (u) against u on a similar piece of paper. The two sheets are now put on top of each other and shifted mutually until the best fit of the data with the theoretical line is found (fig. 7). Then values of $2\sqrt{\frac{kD}{p}}$ can be read from the horizontal shift of the two papers. The vertical shift indicates the part of the hydraulic head required to overcome the radial resistance caused by the fact that the canal does not penetrate the whole aquifer. In our case the rise of the open water level was only effective for 80% so that 20% was used to overcome the radial resistance. Further it was found that $2\sqrt{\frac{kD}{p}} = 100$ hence $\sqrt{\frac{kD}{p}} = 50$. Taking p = 0.2 it follows that kD = 500

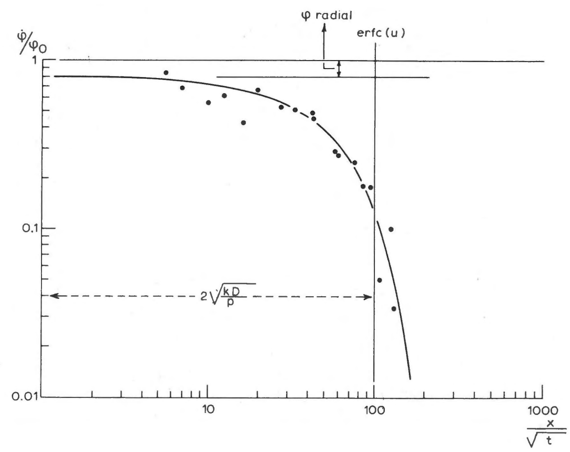


Fig. 7
Curve fitting of $\phi/\phi_o$ values of fig. 6 against $\frac{x}{\sqrt{t}}$

$m^2$/day. Taking into account that at a depth of 15 meters an impermeable layer was present, the hydraulic conductivity of the sand must be 33 m/day.

An example of combining findings of geological borings and hydrological data is given by Scholte-Ubing (Wesseling, 1964). In an area south-west of Utrecht a series of borings had been carried out mainly to determine the thickness of the covering clay and peat layers to get an insight in the seepage occurring in this area. The borings had been finished as observation wells. The piezometric surface map derived from data from these observation wells shows clearly the influence of buried old river channels filled with coarser material and having a very low resistance against flow (fig. 8).

De Ridder and Wit (1967) analyzed seepage flow in the polder "Oude Korendijk" in the south-western part of the country. On the basis of permeability data based on pumping tests, undisturbed samples, textural analysis of drilling samples and the transmission of tidal waves they constructed a map of c-values for the area. Next a map of the differences in potential between the water in the upper layer and that in the water bearing aquifer was constructed (fig. 9). By dividing the area into parts with equal c-values and equal potential differences they applied formula:

$$q_v = \frac{\Delta h_v}{c} \tag{11}$$

for the vertical seepage flow per unit area. Here $\frac{\Delta h_v}{c}$ is the potential difference and c the vertical resistance of the covering layer. This method leads to a flow intensity over the whole polder of 0.32 mm/day. On the basis of inflow of water through the water

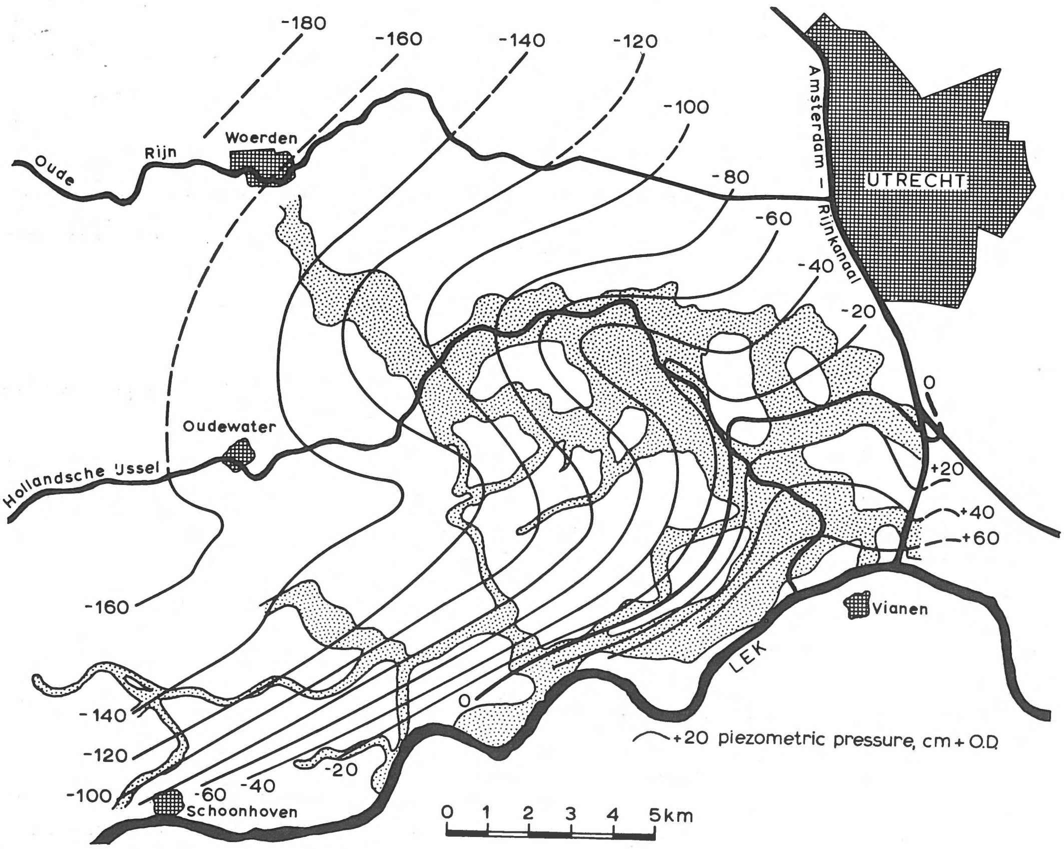


Fig. 8
Map of piezometric pressures in the western part of the province of Utrecht. The map clearly shows the influence of buried old river beds filled up with coarse material (Scholte Ubing).

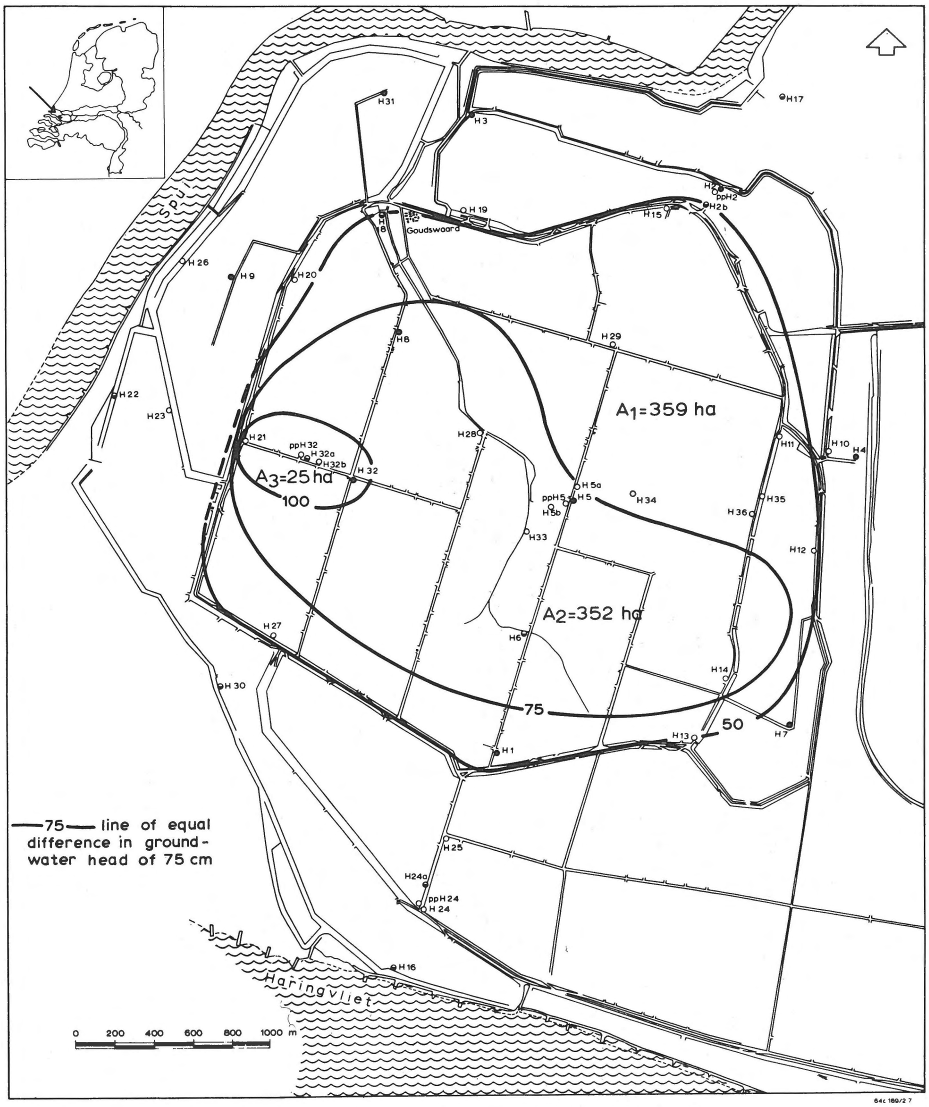


Fig. 9
Contour map of the differences in potential between the mean phreatic level and the mean piezometric level of the upper aquifer in the polder Oude Korendijk (De Ridder and Wit, 1967).

bearing strata they arrived at 0.20 mm/day. The difference must be ascribed mainly to inaccuracies in the c-values used, because this value changed from place to place whereas average values were used for the computation.

The salt supply in this polder due to influent seepage amounted, on the basis of 0.25 mm/day flow intensity, 3.5 kg Cl/ha.day. From water samples and discharge data of the pumping plant a salt inflow between 2.4 and 4.8 kg/ha.day was computed as an average over the year.

## 3.2 *Investigations in the higher part*

In the higher parts of the Netherlands the hydrologic aspects are closely related to the conservation of water for agricultural purposes and the extraction of groundwater for domestic and industrial use. Only the first aspect will be discussed here.

For water conservation purposes a great number of weirs and inlet sluices have been installed in rivulets of this region. Sometimes also a system of small irrigation canals is used. Up to now storage reservoirs are used very seldom because installation of them requires vast areas due to the absence of differences in elevation. To get an optimal distribution of water in space and time a detailed knowledge of the geohydrologic conditions of a watershed or rivulet basin is very important. Some investigations carried out to get more information on this subject will be described.

Ernst and de Ridder (1970) carried out a detailed study of the geohydrologic condition of the Leerinkbeek area located in the eastern part of Gelderland. Besides a map of transmissivities and an isopach map of the quaternary layers a map showing areas with subsurface inflow and subsurface outflow has been constructed. Inflow and outflow have been determined from the above mentioned maps using the equation:

$$v_k A = - \oint q_{ns} \, ds \tag{12}$$

where $v_k$ is the intensity of the net subsurface inflow rate occurring in a square of area A with length s and $q_{ns}$ being the horizontal flow component normal to the sides of the square per unit time. According to Darcy's law:

$$q_{ns} = kD \frac{\partial h}{\partial n} \tag{13}$$

where kD stands for the transmissivity and $\frac{\partial h}{\partial n}$ for the gradient of the phreatic level. The result is given in fig. 10.

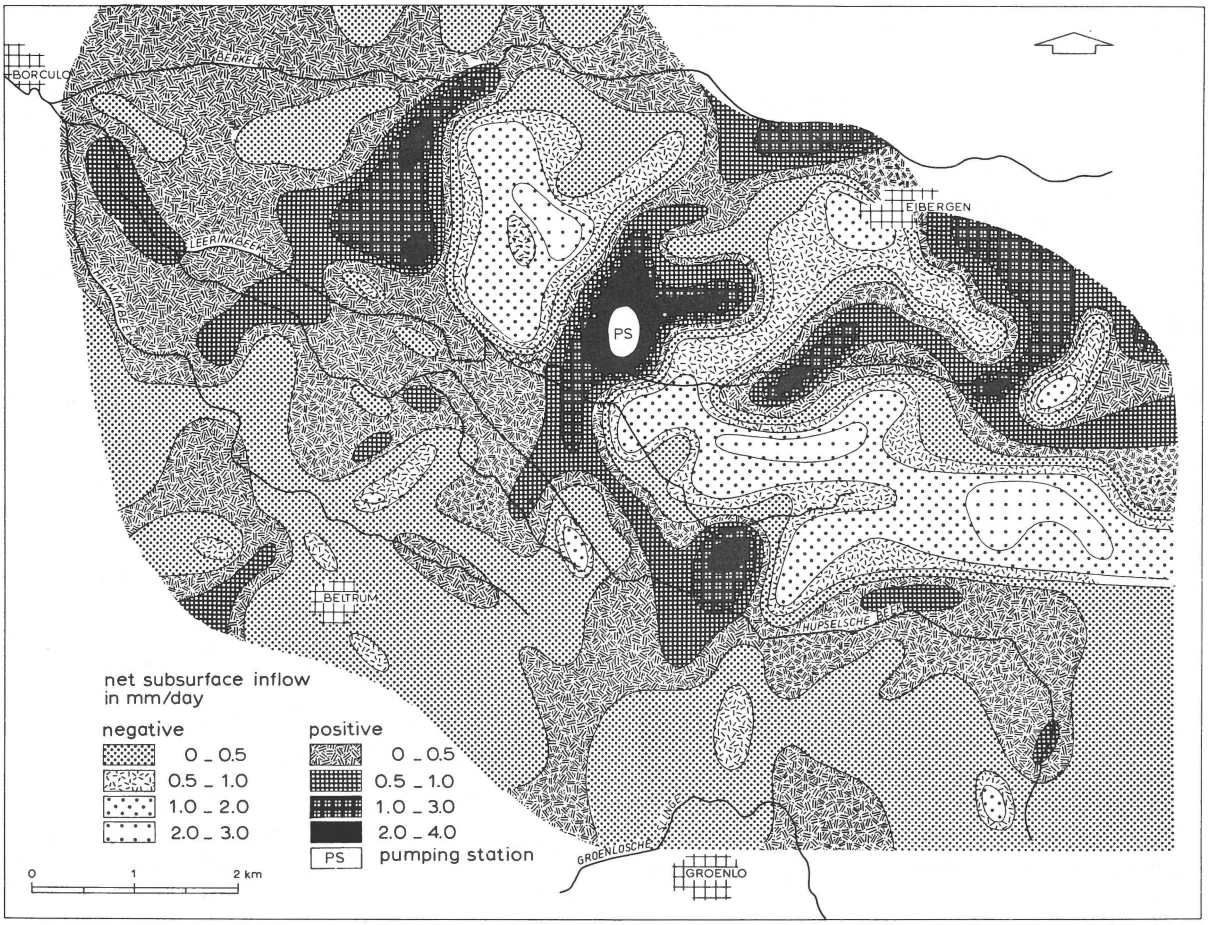


Fig. 10
Influent (a positive kwel) and effluent (negative kwel) seepage in the Leerinkbeek area (De Ridder, 1970).

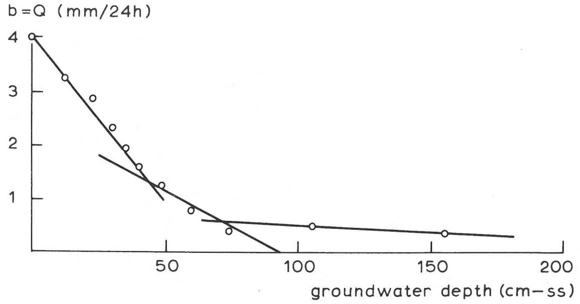


Fig. 11
Joint discharge function after adjustment of six measuring points determined from analyzing groundwater observations (Bloemen, 1970).

Following the same principle Ernst, de Ridder and de Vries (1970) prepared a similar map for the whole eastern part of Gelderland. This type of information gives a valuable insight in the net groundwater flow and is important e.g. for the location of wells for the extraction of groundwater.

Bloemen (1970) describes a method to determine storage, discharge and evaporation from recorded groundwater tables. The analysis is based on the equation:

$$N - gE_o = p.\Delta W + Q \tag{14}$$

where

N = precipitation

$gE_o$ = potential evapotranspiration of a crop according to Penman

Q = total run off

$\Delta W$ = change in water table

p = storage coefficient of the soil

The method holds only when surface flow and interflow are of minor importance. Fig. 11 gives the relation between depth of water table and discharge intensity for six observation points as found from the analysis. For the conservation of groundwater the height of the water level in open water courses can be essential. Ernst (1958) calculated for a catchment in the southern part of the Netherlands the propagation of the rise of the groundwater level for the case the river level is raised over a height $h_o$. Ernst has used in principle the same formula as Edelman (eq. 8). An example of such a calculation is given in fig. 12. Dealing with water distribution problems a detailed knowledge of the water balance of areas with different geohydrological conditions is important too. For the Leerinkbeek area Colenbrander (1970) has prepared these belances for various sub-basins using the equation:

$$E_w = N - Q + (S_b - S_e) + U + I \tag{15}$$

were the symbols not mentioned before stand for the real evapotranspiration ($E_w$); the change in total

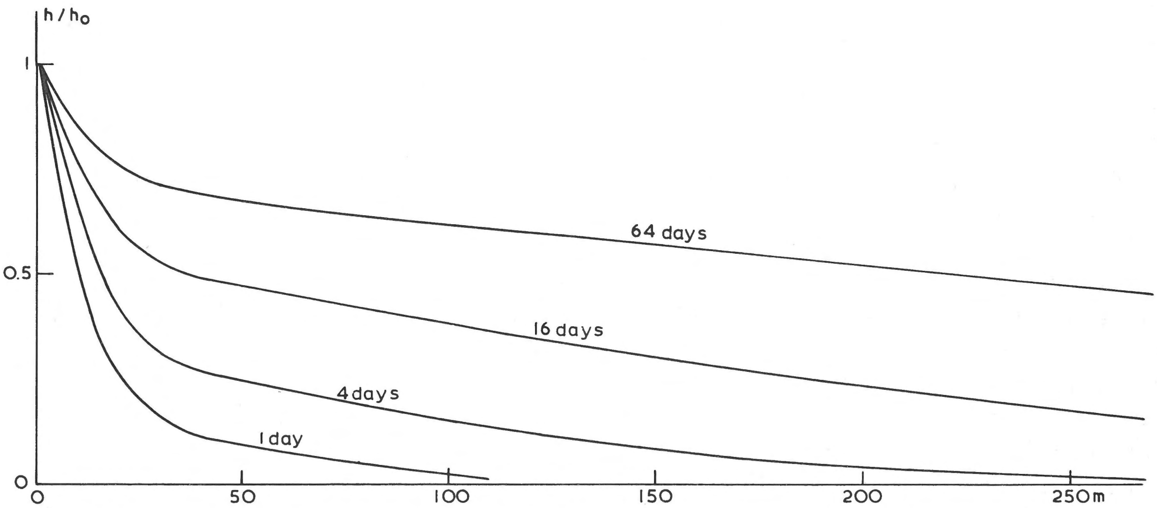


Fig. 12
Rise of groundwater level, at different times after the river level has been raised. (Ernst, 1958).

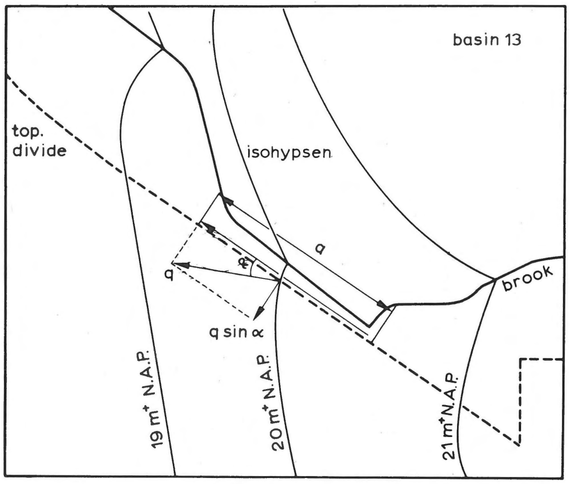


Fig. 13
An example of a basin where the topographic and phreatic water divide are not coinciding and the groundwater outflow has to be calculated (Colenbrander, 1970).

water storage ($S_b - S_e$); the net subsurface inflow (U) and the imported minus exported water (I).

Except ($E_w$) all the other elements were measured directly or determined with the use of geohydrological parameters. Because the topographic and phreatic divides do not always coincide it is advisable to choose the topographic divide as the hydrologic boundary.

The advantage of the method is that the net subsurface inflow (U) can be determined, which is often easier than to measure the flow in a great number of small conduits and to estimate the total discharge of the area. When taking the phreatic divide as the hydrologic boundary one has also to deal with the problem that the phreatic divide can be different during periods with high or low groundwater tables. The net subsurface inflow (U) can be determined with the aid of Darcy's law. Besides the phreatic gradient and the transmissivity also the angle between the direction of groundwater flow and the topographic divide must be taken into account (fig. 13).

In the higher part of the country not only the conservation of water is important, but also the prevention of floods. Due to the geological condition and small discharge capacity of various rivulets flooding occurred frequently. These floods quite often cause considerable damage to agriculture.

In the Leerinkbeek area a detailed flow analysis has been carried out by Colenbrander (1970). Fig. 14 shows hydrographs of basins with different characteristics. The storage capacity of the basins 10, 14 and 12 (which are of about the same size) is increasing in the same order. The relatively high peak flows of basin 12 are caused by a small area with very

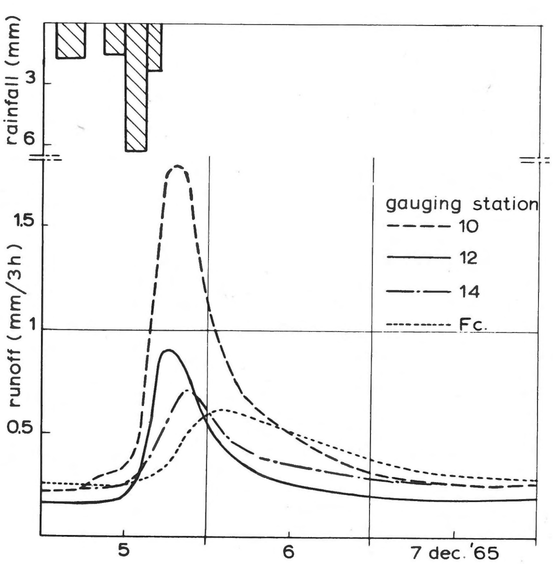


Fig. 14
Hydrographs of 4 separate basins in the Leerinkbeek area (Colenbrander, 1970b).

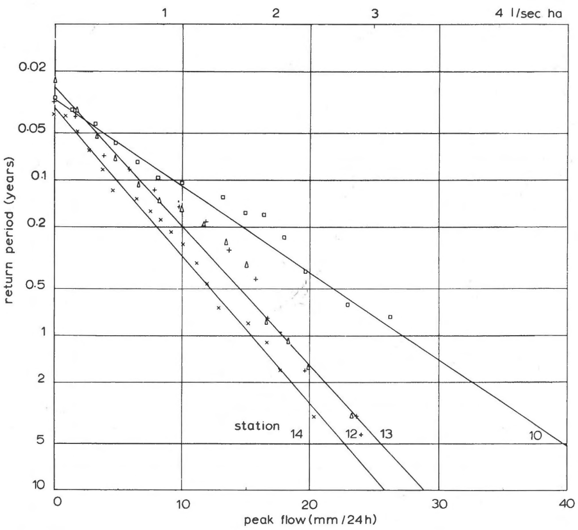


Fig. 15
Return periods for various gauging stations on the average, one execeedance of the given peaks flows (Colenbrander, 1970b).

small storage capacity. At gauging site $F_c$ the discharge of the whole Leerinkbeek area has been measured and besides differences in geohydrological features also a difference in basin size becomes important.

Clearly the geohydrological conditions are affecting the magnitude of peak flow, the shape of the hydrograph and consequently the frequency distribution of peak flow and daily run-off e.g. (fig. 15). Using various geohydrological parameters a number of deterministic rainfall-run-off models have been prepared (d e J a g e r, 1965; d e Z e e u w, 1966 and v.d. N e s and H e n d r i k s, 1971). The hydrographs resulting from a given rainstorm can be derived by these models.

## REFERENCES


Anonymous, (1964) – Steady flow of groundwater towards wells. The Hague 179 pp. Proc. Comm. Hydr. Res. TNO No. 10.

Bloemen, G.W. (1970) – Berging afvoer en verdamping in de Geldersche Achterboek volgens grondwaterstands-analyse. In: Hydr. Onderzoek in het Leerinkgebied (ed. H.J. Colenbrander, H. Wassink, T. Blok en E.W. Schierbeek).

Bosch, H. (1951) – Geohydrologisch Onderzoek Bergambacht. Hydr. Coll. H.C. (S) nr. 255 A. 's-Gravenhage. (mimeographed).

Colenbrander, H.J. (1961a) – Een berekening van hydrologische bodemconstanten uitgaande van een stationaire grondwaterstroming. In: De Waterbehoefte van de Tielerwaard-West, (ed. N.A. de Ridder, T. Blok en H.J. Colenbrander).

(1961b) – Een berekening van de kwel uit de waterbalans. In: De Waterbehoefte van de Tielerwaard-West (ed. N.A. De Ridder, T. Blok en H.J. Colenbrander).

(1970a) – Waterbalansstudies in kleine stroomgebieden. In: Hydr. Onderzoek in het Leerinkbeekgebied (ed. H.J. Colenbrander, H. Wassink, T. Blok en E.W. Schierbeek).

(1970b) – Analyse van afvoergegevens. In: Hydr. Onderzoek in het Leerinkbeekgebied. (ed. H.J. Colenbrander, H. Wassink, T. Blok en E.W. Schierbeek).

Duin, R.H.A. van (1956) – Over de invloed van grondbewerking op het transport van warmte, water en lucht in de grond. Proefschrift LH-Wageningen.

Edelman, J.H. (1947) – Over de berekening van grondwaterstromingen. Proefschrift TH-Delft (mimmiographed).

Ernst, L.F. (1959) – Verhoging van grondwaterstanden en vermindering van afvoer door opstuwing in beken. Versl. en Med. Cie Hydr. Ond. TNO nr. 3; p. 52-71.

Ernst, L.F., N.A. de Ridder en de Vries (1970) – A geohydrologic study of East Gelderland (Netherlands)

Glee, J.P. de, (1951) – Berekeningsmethoden voor de winning van grondwater. Drinkwatervoorziening; derde vacantiecursus Delft. 1951: 30-80. 's-Gravenhage.

Hooghoudt, S.B. (1935) – Bijdr. tot de kennis van enige natuurkundige grootheden van de grond. Nr. 1 's-Gravenhage.

Jager, A.W. de, (1965) – Hoge afvoeren van enige Nederlandse stroomgebieden. Proefschrift LH-Wageningen.

Kruseman, G.P. and N.A. de Ridder, (1970) – Analysis and evaluation of pumping test data. Int. Inst. for Land Reclamation and Improvement, Wageningen, p. 200.

Mazure, J.B. (1936) – Geohydrologische gesteldheid van de Wieringermeer. Rapporten en Meded. Zuiderzeewerken nr. 5: p. 67-131. 's-Gravenhage.

Nes, Th. J. van en M.H. Hendriks, (1971) – Analysis of a linear distributed model of surface runoff. Rep. No. 1. Lab. of Hydraulics and Catchment Hydrology. Agr. Univ. Wageningen, p. 129.

Ridder, N.A. en K.E. Wit, (1965) – A comparative study on the hydraulic conductivity of onconsolidated sediments. J. Hydrol. 3: p. 180-206.

(1967) – Seepage flow analysis of a small polder in the south-western part of the Netherlands. J. of Hydrology 5: p. 47-57.

Ridder, N.A. de (1970) – Hydrologie van het stroomgebied van de Leerinkbeek. In: Hydrologisch Onderzoek in het Leerinkbeekgebied. (ed. H.J. Colenbrander, H. Wassink, T. Blok en E.W. Schierbeek).

(1961) – De bepaling van enige hydrologische bodemconstanten door middel van pompproeven. In: De Waterbehoefte van de Tielerwaard-West. (ed. N.A. de Ridder, T. Blok en H.J. Colenbrander).

Steggewentz, J.H. (1933) – De invloed van getijbeweging van zeeën en getijrivieren op de stijghoogte van grondwater. Thesis TH-Delft.

Wesseling, J. (1958) – Enkele resultaten van de bepaling van hydrologische constanten in het Prunjegebied (Schouwen-Duiveland). Geol. en Mijnbouw 39: p. 624-630.

(1959) – The transmission of tidal waves in elastic artesian aquifers. Techn. Bull ICW, Wageningen nr. 3.

Wesseling; J. and H.J. Colenbrander (1961) – De bepaling van hydrologische bodemconstanten uit de voortplanting van de getijbeweging. In: De Waterbehoefte van de Tielerwaard-West (ed. N.A. de Ridder, T. Blok en H.J. Colenbrander).

Wesseling, J. (1964) – De stroming van het grondwater en de bepaling van de hydrologische constanten. Landb. Tijdschr. 74: p. 934-948.

Wit, K.E. (1960) – Een apparaat voor het steken van ongeroerde monsters in diepe boorgaten. Rapport nr. 10. ICW, Wageningen.

(1962) – An apparatus for coring undisturbed samples in deep bore holes. Soil Sci. 94: p. 65-70.

(1967) – Apparatus for measuring hydraulic conductivity of undisturbed soil samples. Special Tchn. Publ. No. 417. A.S.T.M. p. 72-83.

Zeeuw, J.A. de (1966) – Analyse van het afvoerverloop van gebieden met hoofdzakelijk grondwaterafvoer. Proef-