Drainage of the polder districts in the Netherlands

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WAGENINGEN
THE NETHERLANDS

TECHNICAL BULLETIN 18
1960

ERRATA

page 11.517: 7th line from top: instead of 'that a soil map' read 'a soil map'.

below eq. (1): instead of 'discharge in m^3/day' read 'discharge in m/day'.

page 11.518: eq. (2): instead of 'M' read 'm'.

: eq. (2): instead of 'slw' read 's/W'.

page 11.524: example, 5th line: instead of '$0.e^{-0.38}$' read '$0 \times e^{-0.38}$'.

page 11.526: instead of 'Masland' read 'Maasland'.

: instead of 'Visser, W. C. (1953)' read 'Visser, W. C. (1952)'.

: for the periodical in which this article appeared read instead of 'Versal.', 'Versl.'.

INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE

COMMISSION INTERNATIONALE DES IRRIGATIONS ET DU DRAINAGE

FOURTH CONGRESS R. 27

QUATRIEME CONGRES QUESTION 11

DRAINAGE OF THE POLDER DISTRICTS IN THE NETHERLANDS*

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SUMMARY

In the Netherlands an extensive area of land is only slightly above or even below normal sea level. This area surrounded by dikes is divided into separate polders each with its own water regime. In this low-lying and relatively flat area the influence of the depth of the water table on crop yields is great. The relation between these factors may serve as a base for calculating the desirable depth of drainage within the area, if that a soil map and an elevation map are available.

The capacity of the pumping station may be computed from rainfall frequency analyses, taking into account the seepage from or to adjacent areas.

The whole system of drainage and pumping must be in accordance with each other.

The commonly used drain-spacing equations have been treated. A treatise of analyses of polder discharge is dealt with and a description of a check of the water management in a polder system has been given.

RESUME

Dans les Pays-Bas, une grande superficie de terres n'est que faiblement supérieure ou même inférieure au niveau normal de la mer. Ces régions, entourées de digues, sont divisées en différents polders ayant chacun son propre régime des eaux. Dans cette contrée basse et relativement plate, l'influence de la profondeur des eaux souterraines sur le rendement des cultures est grande. Le rapport entre ces facteurs peut servir de base au calcul de la profondeur de drainage désirable dans la région, si l'on dispose d'une carte des sols et d'une carte d'altitude.

La capacité de la station de pompage peut être évaluée à partir

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d'analyses de la fréquence des précipitations, en tenant compte de l'eau d'infiltration des terrains adjacents ou vers ces terrains.

Le système de drainage et de pompage doit être considéré comme un tout.

L'auteur traite des équations généralement usitées au sujet de l'espacement du drainage, ainsi que de traités d'analyses de l'écoulement des eaux des polders et donne une description de la vérification d'un système de polder.

1. INTRODUCTION

The climate prevailing in the Netherlands is a semi-humid sea climate with moderate temperatures and a normal rainfall of about 700 mm. per year. The evaporation from a free water surface is at a minimum of about 2 mm. in January and reaches a maximum of about 125 mm. per month in June and July. As rainfall is almost evenly distributed throughout the year, there is an excess of drainage water from October up to March. During summer, however, there is a water deficiency and in drier years inlet of water in agricultural areas is necessary in order to prevent depressions in crop yields, especially on lighter textured soils.

Nearly one half of the 2,500,000 ha. of agricultural land is situated only slightly above or even below normal sea level and all this land is protected against flooding by dikes, the first of them were built in the middle-ages. The land in this area is split up in small units, so-called "polders" ranging from 50 to 50,000 ha. Most of them are between 250 and 2,500 ha., the largest being the new Zuiderzeepolders. Superfluous water draining from tile-and ditch drainage systems flows into secondary and main ditches to drainage canals. From these canals it is pumped out into a neighbouring polder, a main canal, a river or the sea (sometimes it is let out by means of sluices into the river or the sea). During summer, water is often let in for cattle drinking water and spray purposes. So each polder has its own water regime which is determined by the combined landowners themselves. A full description of these areas concerning both its history and present situation has been given by Hellinga (1952a).

The aim of the age-old system of polders is to prevent inundation and maintaining the water level in canals and ditches, as well as in the adjacent soil, at a fixed level as accurately as is possible, making the soil suitable for good crop production. As such, it represents a case of reclaimed land in a semi-humid region, that otherwise would be submerged or swampy. During the last decades agricultural and hydrological research has much contributed to a better understanding of the demands that agriculture makes to-day on drainage and water supply. Some results of these investigations and the manner in which they are used in polder design are described in the next sections. First the depth of the ground-water table and its influence on crop yields will be discussed. Then a review will be given of the methods used in drainage design. After that the needed capacity of the pumping stations will be treated. In the last section a description of a method to check the water regime in a polder area will be given.

2. DEPTH OF THE WATER TABLE

Since modern pumping techniques make it possible to maintain a nearly constant water level in each area, much attention has been given to the influence of the depth of the ground-water table on crop yields. In the flat polder areas, which have a moderately shallow water table, this is a very important factor in crop growth. The study of this subject can be handled in different ways. A more or less theoretical treatment including both soil physical properties and climatological conditions has been proposed by Wesseling (1957) and Wesseling and Van Wijk (1955, 1958). Using experimental data three methods can be followed. In the first place it is possible to design experimental fields especially for this purpose. In these fields various depths of the water table are maintained by means of a special drainage system. A description, together with results of such experiments have been given by Hooghoudt (1952) and Van Hoorn (1958). In the second place certain experimental spots may be selected choosing these in such a way, that all circumstances, with the exception of the depth of the water table are the same. Finally, experimental spots can be selected not complying with these conditions, but where the other factors can be integrated into the study of the results by means of a multifactor-analysis. Each method has its own draw-backs, but on the other hand also shows specific advantages. A critical review of these methods has been given by Visser (1952).

Combining all results obtained up to now Visser (1959a, 1959b) obtained the picture given in Figure I. The figures near the curves

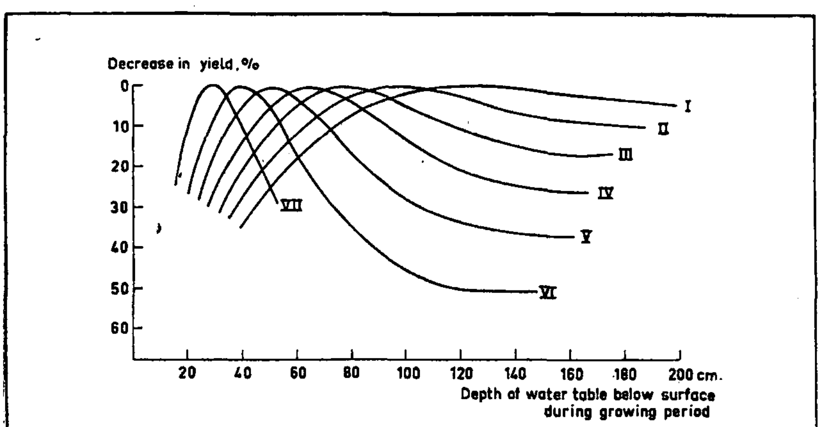

FIGURE 1 :—The relation between yield depression and depth of water table for the various soil types (I-VII) distinguished in the Netherlands,

indicate the soil types distinguished by Dutch soil scientists. These go from heavy textured soils (I) to light textured soils (VI) and peat soils (VII). Because the water-holding capacity of the soil—except for peat soil—is increasing with the soil type number, there seems to be a strong correlation between yield and water-holding properties of the soil. This is in accordance with results of soil physical theories (Visser, 1959a, Wesseling, 1957). The curves must, of course, be considered as giving mean values.

The curves given in Figure 1 may serve as a basis for the determination of the water level that is to be maintained in a polder. For this purpose a soil map showing the different soil types, an elevation map and a map showing the land use must be available. The various soil types are arranged in elevation classes with differences of 10 cm. The total depression in yield is now calculated for different depths of the water table and the final depth is chosen in such a way, that the total yield depression is at a minimum for the whole area. If the variations in elevation, soil type or land use within the polder are too great, the polder is divided into separate sections, each of them having their own water level. The procedure described above is then applied to each section.

As is evident from Figure 1, peat soils have an optimum depth of the water table at approximately 30 cm. The water table in peat soils is maintained mostly on account of their physical and chemical properties instead of in accordance with their water-holding capacity. The water table in these soils must be kept high in order to prevent irreversible drying, decomposition of the organic material and subsidence of the soil. Generally, these soils are used as pasture land. A detailed description of their properties, relcamation and use has been given by Mohrmann (1952).

3. TILE-AND DITCH-DRAINAGE

In order to maintain a low water level in the land between the main and secondary drainage canals, that may be considered as having only a task in the water transport to the pumping station, a detailed ditch-or tile-drainage system is necessary. When a fixed water level is maintained in the ditches, it is by no means sure that the ground-water table will be lowered continuously to this depth, high water tables during short times may occur owing to heavy rainfall, but the water table will fall soon back to its original depth. Because of the great advantages of tile drainage (easier cultivation, no loss of land and less weed control), it is commonly used and ditch-or furrow-drainage is only used in pasture land with shallow water tables. In these soils tile drainage is impossible due to the insufficient hydraulic head.

The simplest drainage system is that one with each tile line directly discharging into a ditch. The system then can be controlled easily and clearing, if necessary, is done very simple by a stream of water brought into the tile by means of a plastic tube connected with a water pump. In general, clay tiles with an inner diameter of 5 cm, and a wall-thickness of

1 cm. are used. The tile lines are given a slope of 10 to 20 cm. per 100 m., except when they are used also for sub-irrigation. In the latter case they are laid down horizontally.

The depth of the tile lines agrees with the desirable depth of the water table and during winter the water level in the ditches is kept 10 to 20 cm. below the outlets.

During the last decades numerous equations describing the steady and non-steady state flow of water in drainage systems have been derived (c.f. Maasland, 1955, Van Schilfgaarde et. al. 1956). One of the most useful solutions regarding steady state flow is that of Hooghoudt (1940). This method, which gives a fairly accurate solution of the problem, is generally used in designing drainage systems in the Netherlands.

Hooghoudt's equation is

$$S=\frac{8k_2d\,m+4k_1m^2}{l^2} \qquad (1)$$

where

- s = discharge in m^3/day
- k_1 = hydraulic conductivity of the layer above drain depth in m/day
- k_2 = hydraulic conductivity of the layer below drain depth in m/day
- l = drain spacing in m.
- m = height of water table above drain level midway between tile lines in m.
- d = thickness of the "equivalent layer" in m., a value depending on drain spacing l, drain radius r_0 and the depth of the impermeable layer below drain depth H.

Values of d, for r_0 ranging from 0·03 to 5·00 m., are given in Hooghoudt's original publication.

The drain spacing is calculated in such a way, that in arable land the water table does not rise above a depth of 50 cm. below surface at a discharge of 0·007 m/day. In the case of grassland the water table should not rise above 40 cm. below surface, during a discharge of 0·007 m/day. For the purpose of drainage design the hydraulic conductivity is determined by means of the auger hole method described by Boumans (1953), Ernst (1950) and Van Beers (1958). As this method measures the hydraulic conductivity of only a small column of soil, it is necessary to repeat the determination on several spots. Generally, 2 to 6 spots per ha. are taken, depending on the size of the project and the homogeneity of the soil (Hooghoudt, 1952).

Hooghoudt's method is very simple, it fails, however, when the soil consists of two layers, the boundary between them not coinciding with the depth of drainage. Therefore, Ernst (1954, 1956) developed a series of equations for one-, two-, three- and four-layer systems. The first of them agrees with equation (1), when $k_1=k_2$. The two-layer system consisting of an upper layer of clay soil, with a relatively small hydraulic conductivity, resting on a sandy layer frequently occurs in the Netherlands. For this system Ernst developed the equation

$$M=SC+\frac{sl^2}{8\ (k_1D_1+k_2D_2)}+slw \tag{2}$$

where the newly introduced symbols mean

D_1 = mean depth of the upper layer in m.

D_2 = mean depth of the lower layer in m.

W = "radial resistance" in days/m, a factor which takes into account the convergence of the streamlines near the drainage centre

$C=\frac{D_1}{k_1}$ = "vertical resistance" of the upper layer in days.

Three cases are distinguished for the calculation of W.

Case A: Tile lines entirely in the upper layer.

$$W=\frac{1}{\pi k_1}\ ln\ \frac{4D_1}{u} \tag{3}$$

where u is the wetted perimeter of the trench in which the tile lines are laid down. Solutions are exact for $k_2/k_1>100$ and approximately accurate for $20<k_2/k_1<100$. If $k_2/k_1<20$ the following equation must be used

$$W=W_o+\log_e\frac{0\cdot25D_1/r}{\pi k_1} \tag{4}$$

where r is the radius of the wetted perimeter of the trench and W_o is the radial resistance when $D_1/r=4$.

Case B: Tile lines coinciding with the boundary between two layers and $b/D_2<0\cdot4$ (b=width of tile trench).

$$W=\frac{1}{\pi k_2}\ ln\frac{4D_2}{u} \tag{5}$$

Case C: Tile lines entirely in the lower layer.

$$W=\frac{1}{\pi k_2}\ ln\ \frac{D_2}{u} \tag{6}$$

The criteria for s and m are the same as those for equation (1).

4. THE CAPACITY OF THE PUMPING STATION

During wet periods, rainfall may be as high as 30 to 50 mm. per day. It is not necessary, however, to install pumping stations of this capacity, as no harm will be done by a too high level of the water for a few days only. The experience learned is that the pumping capacity must be 8 to 12 mm/day. A method to determine whether the pumping capacity of a certain polder is great enough, will be described in the following section. As a basis for the determination of the capacity of a pumping station, analyses of rainfall frequency may serve. An example of such a kind of investigation is given in Figure 2 for which data from Visser (1953) were

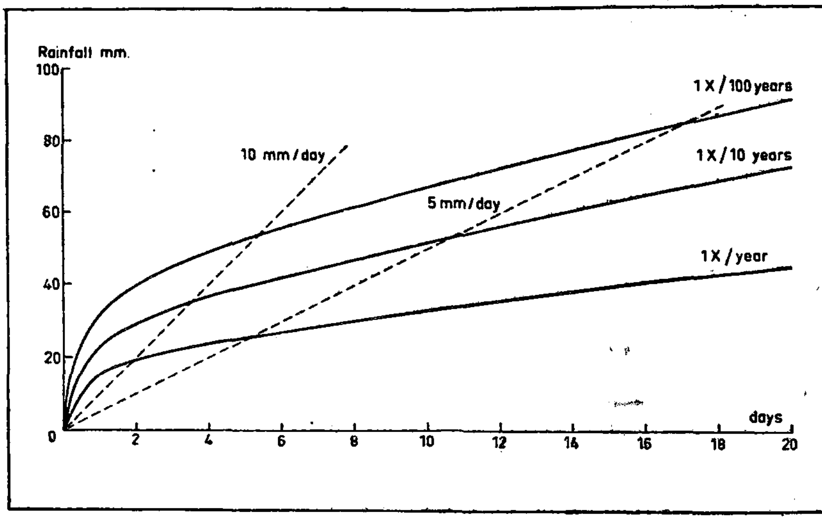

FIGURE 2—Probability of the amount of rainfall in a specific time. The dotted lines give pumping capacities.

used. In this figure the rainfall frequencies which can be expected once per year, once per 10 years and once per 100 years are given. Generally, a probability of once per 10 years will be taken in polder design. The dotted lines in Figure 2 indicate the capacity of certain pumping stations, these being 5 and 10 mm/day respectively. In the former case, it will last approximately 11 days before all rain fallen on the polder is removed by the pumping station. In the latter case, however, all rainfall will already be removed in 3·5 days.

In order to get a result as reliable as possible, the evaporation must be included in the rainfall frequency analysis. Various examples of analyses of the difference between rainfall and evaporation for both winter and summer periods have been given by Stol (1958). Applying the procedure described above, it remains difficult to account for the effect of the excess of water on crop growth, and therefore, high water levels, during short periods. In a polder a certain storage is always present, depending on size and number of the ditches, the type of soil and its use, and the location of the polder. Furthermore, the excess can be diminished by pumping as soon as rain starts falling.

Seepage from adjacent polders or open water has to be taken into account too. This factor can be determined from data on soil permeability, thickness of permeable layers and differences in hydraulic head (Mazure, 1936).

5. DISCHARGE FROM A POLDER AREA

Although the pumping station and the ditch and canal system of the polder may have a capacity that is sufficient for the area concerned, it is possible that the system does not work in the way that was expected beforehand. When the drainage system of the polder is insufficient, the discharge may be too small for the pumping station to exploit its full capacity. In general, it may be stated that the discharge from a polder area is limited by the drainage system and the duration of the pumping will have to be adapted to it. It is necessary, therefore, to know the exact discharge of a polder area.

It may be stated that the discharge from a drained area is linearly related with the hydraulic head, the latter measured from the drainage base, thus

$$s = \alpha m \tag{7}$$

where α is a constant dependent on the efficiency of the drainage system of the area and the physical properties of the soil. The increase in hydraulic head of the water within the polder area depends on the difference between net-infiltration rate and discharge according to

$$n\ dm = (s_1 - s)\ dt \tag{8}$$

where dm and dt stand for small increments of m and t ; n is the storage capacity of the soil and s_1 is the net-infiltration rate (rainfall minus evaporation). Substituting now equation (7) into equation (8) gives

$$\frac{n}{\alpha}\ ds = (s_1 - s)\ dt \tag{9}$$

Dividing now each rainshower in such a way that intervals of constant infiltration rate occur, the following, derived by integrating equation (9), is valid for each time interval t_n

$$\left[\frac{n}{\alpha}\ ln\ (s - s_1)\right]_{s_{t-1}}^{s_t} = -t \tag{10}$$

$$s_t = s_{t-1}\, e^{-\alpha/nt} + (1 - e^{-\alpha/nt}) s_1 \tag{11}$$

Taking $\frac{\alpha}{n} = \beta$, the equation proposed by De Zeeuw and Hellinga (1958)

$$s_t = s_{t-1}\, e^{-\beta t} + (1 - e^{-\beta t}) s_1 \tag{12}$$

is obtained. This equation means that the outflow in a certain period depends on the outflow of the foregoing period, on the infiltration rate s_1 and on the discharge factor β. Taking Hooghoudt's drainage equation (1) in its simplest form, in this way omitting the flow in the upper layer, we get

$$s = \frac{8\ K\ md}{l^2} \tag{13}$$

Evidently α in equation (7) then will be

$$\alpha = \frac{8\ Kd}{l^2}$$

and therefore (14)

$$\beta = \frac{\alpha}{n} = \frac{8\ kd}{l^2} \cdot \frac{1}{n}$$

In order to account for the elliptic shape of the ground-water table, De Zeeuw and Hellinga proposed to introduce in equation (14) a term $\frac{4}{\pi}$, so that for drainage systems

$$\beta = \frac{8\ Kd}{l^2} \cdot \frac{4}{\pi n} \tag{15}$$

Hellinga (1952) applied the theory on polder areas. Various examples of calculating β from drain outflow measurements are given by De Zeeuw and Hellinga (1958). When β is known, the discharge from a polder area can be determined for various rain-showers.

6. CHECK OF THE WATER MANAGEMENT IN A POLDER AREA IN THE SOUTH-WEST OF THE NETHERLANDS

A polder area consisting of light clay soils, having an area of 3,200 ha., was served by a diesel-engine pump with a capacity of 8 mm/day. As the question arose, whether this capacity was sufficient for this area, a check of the discharge of the polder was planned. The measurements carried out during the period February 13 to March 7, 1956 included the collection of

1. ground-water table depths at 65 spots spread out regularly over the polder area
2. polder levels on 33 spots within the area
3. rainfall data taken at 4 places
4. the amount of water pumped out of the area.

Besides the observations mentioned above, there were available

1. ground-water table heights at 45 of the 65 spots, measured four times a year from 1952 to 1956
2. polder levels at 18 from the 33 spots, measured during 16 years
3. a polder map with all drainage canals and ditches, showing the flow direction of the water
4. an elevation map of the area
5. a soil map of the area.

During the period from the 13th to the 21st of February daily observations were carried out, while in the period February 21 to March 7 these observations took place 2 to 3 times a week.

From the long-time observations of the water table some spots were selected to serve as a basis for further analyses. All other water-table observations were plotted against those of the selected spots. From these so-called "fluctuation diagrams", showing the regression between an arbitrarily chosen spot (Figure 3) and a selected spot and the mean depth

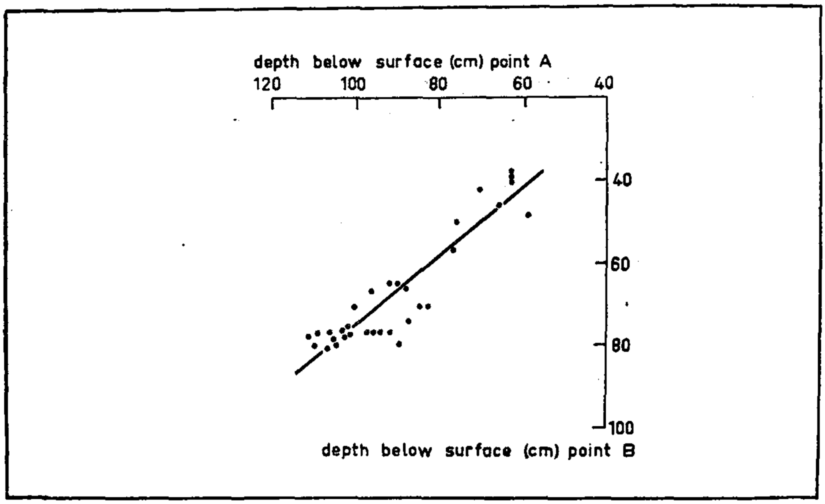

FIGURE 3:—The correlation between the depth of the water table at two different spots.

of the water table in the long-time observations, the mean depth of the water table during the summer and winter period, as well as their fluctuations, could be mapped. The same could be done for the polder levels. The difference in height between polder level and ground-water table showed clearly the drainage possibilities of the polder and the places where it was insufficient. The gradient of the polder level in the direction of the pumping station and the fluctuations in this level clearly showed in how far drainage canals and ditches were large enough.

The amount of water pumped out of the area was determined from the hours of pumping and the capacity of the pump. For this purpose a pumping characteristic was constructed from outflow measurements of the pump. A pumping period of 3·14 hours was equivalent with 1 mm. water height over the whole area. With the aid of these pumping hours and rainfall data, the discharge factor β was determined in the following way. From Figure 4, showing the rainfall data and pumping hours, two periods were selected namely from February 14 to 23 and February 26 to March 3.

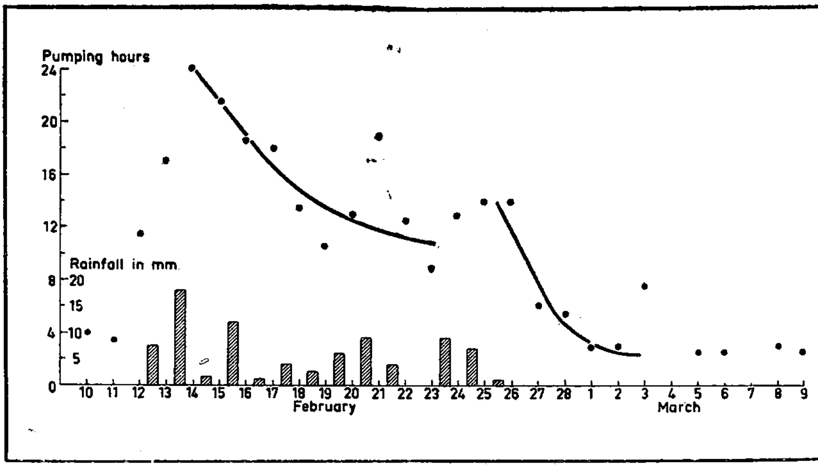

FIGURE 4 :—Amount of rainfall and pumping hours for the polder area under discussion, during the period February 10 to March 9.

First period

maximum discharge = 7·6 mm/day (24 pumping hours)
s_1 = rainfall minus evaporation = 4·8 — 0·3 = 4·5 mm/day
Taking $\beta t = 1$ in equation (12), gives the result
$s_t = 7 \cdot 6 \times 0 \cdot 386 + 4 \cdot 5 \times 0 \cdot 632 = 5 \cdot 64$ mm/day

The value of s_t is equivalent, therefore, with $5 \cdot 64 \times 3 \cdot 14 = 17 \cdot 7$ pumping hours. Drawing a smooth curve through the points of Figure 4 the time needed to reach $s_t = 5 \cdot 64$ mm/day can be read, this being 2·6 days. Since $\beta t = 1$ and $t = 2 \cdot 6$, $\beta = 0 \cdot 38$.

Second period

maximum discharge $s_0 = 3 \cdot 8$ mm/day (11·8 pumping hours)
s_1=rainfall minus evaporation=0—0·5=—0·5 mm/day
Taking again $\beta t = 1$, eq. (12) gives

$$s_t = 3 \cdot 8 \times 0 \cdot 386 - 0 \cdot 5 \times 0 \cdot 632 = 2 \cdot 11 \text{ mm/day}$$

This value is equivalent with $3 \cdot 14 \times 2 \cdot 11 = 6 \cdot 6$ hours of pumping. As can be read from Figure 4 this will be reached after 1·3 days. So $\beta = 0 \cdot 38$.

The factor β, computed from earlier periods for which pumping hours were known, was smaller than those for the above two periods. The reason for this fact is, that before the measuring period there was water flowing from adjacent areas into the area through culverts. These were closed during the measuring period. From drain discharge measurements on experimental fields lying in a similar area, however, it was possible to compute β in the same way. The results are given in Table I. The mean value is also 0·38.

TABLE I

Values of β calculated from drain discharge measurements

No. of field	1	2	3	4	5	6	7	8
β	0·30	0·43	0·42	0·48	0·26	0·45	0·36	0·33

With the aid of equation (12), in which β was taken 0·38 and known rainfall and evaporation, day-by-day discharge was calculated for the last 26 winter periods. The calculations involved are demonstrated by the following example.

Example

On October 3 the discharge was zero. On October 4 rainfall was 14·7 mm. and evaporation 0·9 mm., giving for $s_1 = 14{\cdot}7 - 0{\cdot}9 = 13{\cdot}6$ mm/day. The discharge on October 15 was, therefore, according to equation (12) ($t=1$, $\beta=0{\cdot}38$):

$$s_t = 0 \cdot e^{-0.38} + 13{\cdot}6\left(1 - e^{-0.38}\right) = 4{\cdot}14 \text{ mm/day}$$

On October 5 rainfall was 4·3 mm. and evaporation 0·9 mm. So $s_1 = 4{\cdot}3 - 0{\cdot}9 = 3{\cdot}4$ mm. and discharge on October 6

$$s_t = 4{\cdot}14\, e^{-0.38} + 3{\cdot}4\left(1 - e^{-0.38}\right) = 3{\cdot}9 \text{ mm/day}$$

Next the capacity of the pumping station was set at three values, respectively 7, 8 and 9 mm/day. It was further supposed that the excess of drainage water was pumped out to the maximum capacity of the pumping station. The amount left in the polder was then taken into account for the calculation of the discharge of the next day. The results obtained in this way were subjected to various mathematical analyses. One of the results is given in Table II.

TABLE II

Number of subsequent days on which the discharge from the polder was larger than the pumping capacity

number of days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
capacity in mm/day 7	12	14	7	4	3	3	3	0	0	0	1	1	1	0	1
8	13	16	7	4	4	2	0	0	0	0	0	0	0	0	0
9	19	1	6	3	0	0	0	1	0	0	0	0	0	1	1

The probability that the discharge during a certain number of subsequent days will exceed the capacity of the pumping station was also computed. The result is given in Table III.

TABLE III

Probability of discharge exceeding a pumping capacity of 7 mm/day

amount of subsequent days ..	4	5	6	7	8	10	14
Probability in % ..	62	54	46	38	31	18	4

A method to determine the effect of various excess of rainfall, left in the polder during shorter or longer periods, on soils and crops will have to be worked out in order to judge, to what extent they are allowable.

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