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Calculation of drain spacings for optimal rainstorm flood control

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Abstract

In many parts of the world the frequency of river floods (flash floods) seems to have increased during the past half century. Intensified agriculture is considered as a possible cause for the changed peak flow behavior. It is believed that a large-scale, narrowly designed subsurface drainage reduces the soil water retention in periods with excessive precipitation or snow melt. To increase the soil water retention, it may be necessary to reconsider conventional drain spacing design. The present study deals with the calculation of drain spacings for optimal rainstorm runoff control. A semi-analytical procedure is developed with which for a given extreme rainfall event the drain spacing is calculated that provides the highest possible soil water retention, but no surface runoff. The model considers two-dimensional unsteady water flow between parallel tile drains, with a rising water table. It combines an analytical rising water table model with an empirical spreading water table model. A comparison of the new and a conventional drain design system (Hooghoudt–Ernst) shows that with the newly designed system a considerable temporary soil water retention during heavy rainfall can be achieved. For example, for a soil with a hydraulic conductivity of 0.5 m d^{-1} that is underlain by an impervious barrier at the 2.0 m depth, and that is drained by tiles with a radius of 0.1 m at the 1.0 m soil depth, an additional soil water retention of 38 mm is obtained when the drain spacing is 46.0 m instead of 13.5 m for a rainfall event of 80 mm in a 4-day period. The newly proposed design system may help to reduce the flood threat in areas with large-scale agricultural drainage in periods with excessive rainfall or snow melt.

Keywords: Subsurface drainage; Drain model; Catchment hydrology; Peak flow; Stormwater runoff control; External costs of agriculture

1. Introduction

Agricultural land drainage at a large scale has been practiced in Northwestern Europe since the middle of the 19th century. In Goudie (2000) an overview about the present degree of drained agricultural land in that part of the world is given. His map shows, for example, that in the United Kingdom 60.9% of the agricultural land is drained, in the Netherlands 65.2%, in Denmark 51.4%, and in Finland 91.0%. For former West Germany Goudie (2000) indicates a drainage percentage of 37% and for former East Germany 27.0%. Surprisingly high is the drainage percentage in Hungary (73.7%).

The first drain spacing equations were derived also in Northwestern Europe (van der Ploeg et al., 1999c). Until the middle of the 20th century, mainly drain spacing equations for steady-state flow conditions were derived; since 1950 drain formulas for non-steady-state flow conditions have also been developed increasingly. The development of drain spacing design criteria from 1850 to 2000 is well documented by the three monographs of the American Society of Agronomy (ASA) and the American Society of Agronomy/Crop Science Society of America/Soil Science Society of America (ASA/CSSA/SSSA) on the drainage of agricultural land, i.e. by Luthin (1957),

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van Schilfgaarde (1974a) and Skaggs and van Schilfgaarde (1999). The main design criterion during the past 150 years of scientific drainage was the water table height, midway between two adjacent drains, above some impervious barrier. Either a steady-state water table, or a falling water table was considered in the flow analysis. In both cases the objective was to establish or maintain optimal physical growing conditions in the root zone of the crops grown on the field.

To remove excess rain or irrigation water as fast as possible from the root zone of a growing crop, it is necessary to have small drain spacings. In Germany, subsurface drainage systems are designed with use of the Hooghoudt–Ernst equations (Eggelsmann, 1981; van der Ploeg et al., 1999b). When the design rainfall is chosen high, the Hooghoudt–Ernst equations result in small drain spacings. Standard rainfall rates in Germany are 7 mm d^{-1} for areas with an annual precipitation of less than 600 mm, 9 mm d^{-1} for such with 600–1000 mm, and 17 mm d^{-1} for regions with more than 1000 mm of precipitation per year. Recommended rainfall rates, however, are generally higher and vary between 10 mm d^{-1} for the coastal area of Northern Germany, and 24 mm d^{-1} for the pre-Alp region of Southern Germany (van der Ploeg et al., 1999b). In such cases a narrowly spaced drainage system is designed that is highly effective in removing surplus soil water in periods with excessive rainfall. With about one fourth of its total agricultural land area tile-drained, Germany thus has a highly effective, large-scale soil drainage system.

However, this system has recently been questioned. Particularly in Western and Southern Germany, it appears that the frequency of river floods has increased during the past few decades (van der Ploeg et al., 1999a, 2001b). Although a combination of factors, such as climate change, decrease of the meadowland area, physical soil degradation of the cropland area, increased cultivation of runoff-enhancing crops, is considered to be responsible for the observed change in river discharge behavior (van der Ploeg et al., 1999c, 2001a,b), it is argued that the large-scale, narrowly designed subsurface drainage of agricultural land also, possibly contributes to the flood problem. Although a narrowly designed subsurface drainage system may reduce surface runoff, it is believed that in periods with heavy or prolonged rainfall the drain discharge increases disproportionally.

The discussion about the role of artificially drained land in the discharge behavior of rivers is not new. In Germany, for example, this subject was discussed by early scholars such as Hess (1879), and particularly by Krause (1898). The discussion has been controversial since the beginning. Whereas some argue that land drainage reduces, by increasing the soil water storage capacity, the threat of river floods, others believe that because of a loss of soil flow resistance, the flood risk due to soil drainage increases. A thorough study on this subject has been made by Robinson (1990) and Robinson and Rycroft (1999). These authors have clearly demonstrated the complexity of the matter and have shown additionally that a general answer to the question, as to whether drained land in a catchment enhances or reduces the discharging river's flood peak during a rainstorm, cannot be given. However, at the field scale it appears that flood peaks are frequently decreased by subsurface drainage in areas that prior to drainage had a high water table. In case of heavy or prolonged rainfall, surface runoff often occurs in such areas. By lowering the water table, an increased soil water storage capacity reduces surface runoff as well as the following flood peak. If, on the other hand, the ground water table in the undrained state was deeper and rarely causing surface runoff, flood peaks frequently increase after drainage because of a shortened subsurface flow path for water.

In addition to subsurface drainage, often the discharging drainage ditches and canals are deepened and straightened. In such cases, a flood peak increase has been observed at the catchment scale, even if subsurface drainage itself enhances a flood peak decrease. Because channel improvements have been carried out in many land drainage projects in Germany (van der Ploeg and Sieker, 2000), it can be assumed that agricultural drainage generally is contributing to the flood problem that Germany presently is facing.

In the present study the design of subsurface drainage systems is reconsidered. Not the root environment of a growing crop, but a maximum soil water retention in periods with excessive rainfall, snow melt or irrigation, will be of main concern. For a rainstorm of given intensity and duration (design recharge), that particular drain spacing L is searched, for which the soil between the drains becomes completely water-saturated at the moment the recharge stops. The objective thus is to design a drainage system that provides maximum soil water retention, but that does not allow surface runoff for a given design recharge. To this end, a semi-analytical model, describing the water table rise between drains during a rainstorm, will be extended, and sample calculations with the extended model will be carried out and evaluated. For earlier work on this subject, a reader is referred to Zimmer et al. (1995), Lesaffre and Zimmer (1988) and Salem and Skaggs (1998), and in particular, with respect to runoff control, to Skaggs (1980).

2. Model considerations

We are going to present a two-dimensional drainage model, with which the discharge q from a subsurface tube (tile) drain can be calculated. The model applies to flat or slightly sloping land (Ritzema, 1994). We will consider non-steady flow conditions in a homogeneous and isotropic soil, underlain by an impervious horizontal or slightly sloping barrier, and drained by parallel, equally spaced tube drains, two of which are shown in Fig. 1.

Although we will consider non-steady flow conditions, it is useful to consider first briefly steady-state flow conditions. A schematic representation of the flow region is shown in Fig. 1.

In case of steady-state flow conditions, the discharge rate q from a drain can be calculated with the Hooghoudt equation, which can be written (van der Ploeg et al., 1999c) as

$$q = \frac{8Kdh}{L^2} + \frac{4Kh^2}{L^2}, \qquad (1)$$

where K stands for the soil hydraulic conductivity at saturation, h is the height of the water table above the drain level (Fig. 1), midway between the drains, L is the drain spacing, and d stands for the water depth in a fictitious ditch, that would be just as effective in removing soil water as a tube drain of radius r at a distance D above the impervious boundary. For

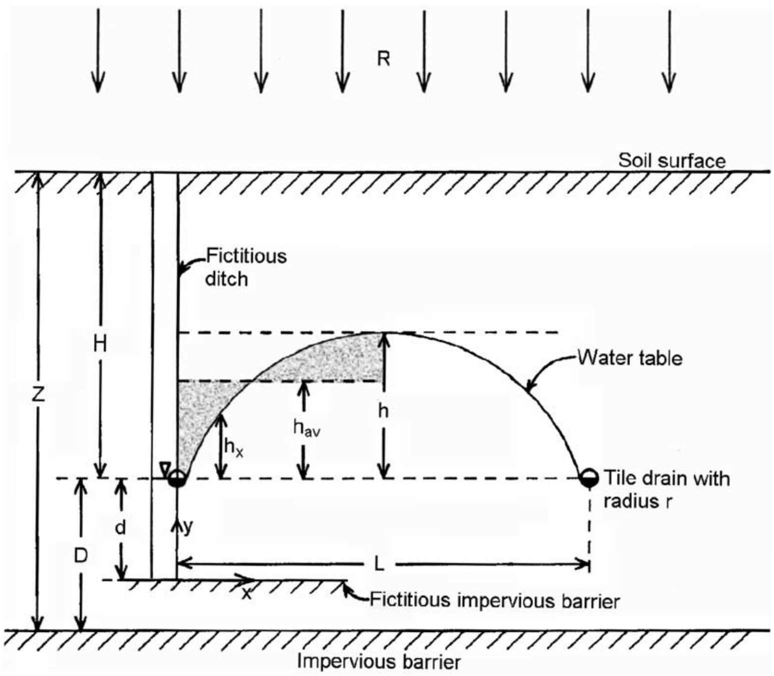

Fig. 1. Schematic representation of a homogeneous soil, underlain by an impervious boundary, that is drained by parallel, equally spaced tubes (tiles), two of which are shown.

a discussion of d, we refer to van der Ploeg et al. (1999b,c). It is noted, that for steady-state flow conditions the drain discharge q is equal to the recharge (rainfall) rate R, shown in Fig. 1.

For later use, the equation for the shape of the water table in Fig. 1, as well as for the average (flat) water table height h_{av}, are given here. With use of a cartesian coordinate system (Fig. 1), the height y of the water table at any location x between the drains can be calculated from the expression (van der Ploeg et al., 1999b)

$$y^2 - d^2 = (q/K)(Lx - x^2), \tag{2}$$

from which it follows (because $y = h_x + d$) that the height h_x of the water table above the level of the tube drains at any location x between the drains is given as

$$h_x = \sqrt{(q/K)(Lx - x^2) + d^2} - d. \tag{3}$$

From the space-variable water table height h_x, the average water table height h_{av} above the level of the drains can be calculated as

$$h_{av} = \int_0^L h_x dx/L. \tag{4}$$

With use of Eq. (3), h_{av} can thus be expressed as

$$h_{av} = \frac{qL^2 + 4Kd^2}{4L\sqrt{qK}} \tan^{-1}\left(\frac{L}{2d}\sqrt{\frac{q}{K}}\right) - \frac{1}{2}d. \tag{5}$$

This expression for h_{av} is valid for $h \leq H$, where H is the depth of the drains below the soil surface (Fig. 1). When in Eq. (5) the right-hand side (RHS) of Eq. (1) is substituted, Eq. (5) reduces to

$$h_{av} = \frac{(d+h)^2}{2\sqrt{h(2d+h)}} \tan^{-1}\left(\frac{\sqrt{h(2d+h)}}{d}\right) - \frac{1}{2}d. \tag{6}$$

In case of non-steady flow conditions, the height h of the water table is calculated with use of the equation (Lesaffre and Zimmer, 1988; Zimmer et al., 1995)

$$C\mu\partial h/\partial t = R - q, \tag{7}$$

where C is a water-table shape factor, μ represents the drainable porosity, t is time, R is the recharge rate, and q is the rate of drain discharge. Eq. (7), with different expressions for q, has been used by various authors to derive non-steady-state drainage equations (van Schilfgaarde, 1974b). Following Lesaffre and Zimmer (1988) and Zimmer et al. (1995), we used in our analysis the RHS of Eq. (1) to express q. Substituting the RHS of Eq. (1) for q in Eq. (7) and solving this equation, one can express the height h_t of the water table, midway between the drains, as follows

$$h_t = \frac{a}{2K}\tanh\left[\frac{2ta}{L^2 C\mu} + \tanh^{-1}\left(\frac{2K(d+h_0)}{a}\right)\right] - d, \tag{8}$$

where the factor a is given by

$$a = \sqrt{RL^2K + 4K^2d^2}$$

and where h_0 is the water table height at $t=0$, midway between the drains (Fig. 2), when the rainstorm starts. Also this expression is valid for $h_t \leq H$ (Fig. 1). From Eq. (8) the time $t=t_1$ can be calculated, at which the water table reaches the soil surface (i.e. when $h_t=H$). This value $t=t_1$ depends (as Eq. (8) indicates) on the drain spacing L.

The non-steady-state drain discharge rate q is calculated (Lesaffre and Zimmer, 1988; Zimmer et al., 1995) as

$$q = A\left(8\frac{Kdh}{L^2} + 4\frac{Kh^2}{L^2}\right) + (1 - A)R, \tag{9}$$

where A is another water-table shape factor. Eq. (9) shows, that the drain discharge q for non-steady-state water table conditions is calculated from a sequence of steady-state water tables. However, because the water table is not rising at the same rate at every location, a portion of the recharge rate, $(1 - A)R$, is directly contributing to the drain flow. Substitution of h_t of Eq. (8) in Eq. (9) yields for the drain discharge rate q_t :

$$q_t = A\left(\frac{8Kdh_t}{L^2} + \frac{4Kh_t^2}{L^2}\right) + (1 - A)R. \tag{10}$$

The shape factors A and C in Eqs. (7)–(10) depend primarily on the fictitious depth d. For a steady-state water table and for $d = 0$, the parameter $A = 0.869$ and $C = 0.904$, whereas for $d = \infty$, $A = 0.8$ and $C = 0.833$. For intermediate values of d, A and C depend also on h (Zimmer et al., 1995). For a rising water table, these shape factors A and C strictly speaking do not apply, because of an initial arching of the water table near the drains. The steady-state water-table shape, for which A and C apply, is only approached in the course of

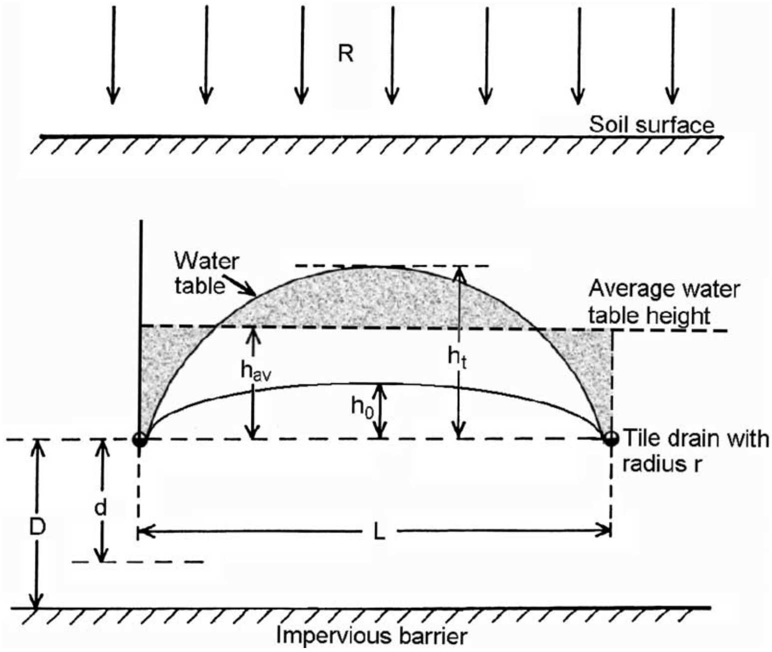

Fig. 2. The water table between two tile drains in case of a rising water table; the height of the water table midway between the drains at time $t = 0$ is denoted by h_0 and at some arbitrary time t by h_t.

the recharge process. This dynamic behavior of the water table can be described only numerically (Bouarfa and Zimmer, 1998). In our approximate analysis, however, we assumed a steady-state shape of the water table throughout the rising process.

As soon as the water table (h_t in Fig. 2) reaches the soil surface (at $t = t_1$), Eq. (8) does not apply any longer and neither do Eqs. (9) and (10) for the drain discharge. From this time on, an empirical relation proposed by Salem and Skaggs (1998) can be used to estimate the drain discharge q, whilst the soil profile is further filling up. Referring to Fig. 2, we can write this relation as

$$q = q_2 - (q_2 - q_1)\exp\left(\beta \frac{h_{av} - h_{1,av}}{h_{av} - h_{2,av}}\right), \tag{11}$$

where h_{av} is the the average (but initially unknown) water table height (Fig. 2), $h_{1,av}$, the value of h_{av} when the water table reaches the soil surface (at $t = t_1$), $h_{2,av}$, the value of h_{av} when the soil becomes fully saturated (at $t = t_1 + t_2$), and q, q_1, and q_2 are the corresponding drain discharge values. In Eq. (11), β is a matching factor, that will be discussed later.

The quantity q_1 in Eq. (11) can be determined with Eq. (9), for $h = H$. The parameter q_2 in Eq. (11) is the drain discharge (m^3 m^{-2} d^{-1}) per unit length (L) of drain, in case the soil profile is completely water-saturated (ponded case with a zero height of water standing on the soil surface). For such a flow configuration, Kirkham (1957) has provided a solution (his equation III.39), from which our drain discharge q_2 can be derived. Using that equation, we can express q_2 as (Kirkham, 1957)

$$q_2 = 4\pi K(H - r)/(fL) \tag{12}$$

where the function f can be written as (Fig. 1)

$$f = 2\ln\left\{\frac{\sinh[\pi(2H - r)/L]}{\sinh(\pi r/L)}\right\} - 2\sum_{n=1,2,\ldots}^{\infty} (-1)^n \times \ln\left\{\frac{\sinh^2(2\pi nZ/L) - \sinh^2(\pi r/L)}{\sinh^2(2\pi nZ/L) - \sinh^2[\pi(2H - r)/L]}\right\}. \tag{13}$$

In Eq. (13) the symbol Z stands for the depth of the impervious barrier below the soil surface ($Z = H + D$, see Fig. 1). The other symbols in Eqs. (12) and (13) have been defined above.

To compute the discharge rate q with Eq. (11), values for h_{av}, $h_{1,av}$, and $h_{2,av}$ must be known. As can be seen from Fig. 2, $h_{2,av} = H$. The parameter $h_{1,av}$ is given by Eq. (6), with $h = H$ (Fig. 1). The value for h_{av} in Eq. (11) is not easily available, but can be derived from the expression

$$R - \mu\frac{dh_{av}}{dt} = q_2 - (q_2 - q_1)\exp\left[\frac{\beta(h_{av} - h_{1,av})}{(h_{av} - h_{2,av})}\right]. \quad (14)$$

This differential equation cannot be solved analytically, but must be solved numerically. The numerical solution provides the time $t=t_2$, for which the average water table height h_{av} becomes equal to H (Fig. 1). At this moment ($t=t_2$) the soil becomes water-saturated. As can be seen from Eqs. (8) and (10), the value of $t=t_2$ depends on the drain spacing L.

Once the value t_2 is known, the sum $t_1 + t_2$ can be compared with T (the duration of the rainstorm). In case $t_1 + t_2 < T$, the soil became saturated too early and a new (smaller) estimate for the drain spacing L must be made. For the new value of L the procedure to estimate t_1 and t_2 (and the optimum value for L) starts all over, i.e. new values for q_1, q_2, and $h_{1,av}$ have to be calculated before Eq. (14) is numerically solved again. For selected problems, we will show how the combined model can be used to design a drainage system that prevents surface runoff and provides maximum soil water retention in case of heavy rainfall.

3. Materials and methods

The drainage area considered in this study is the catchment of the Leine river in Northern Germany. The Leine river is a tributary of the Aller river, which in turn is a tributary of the Weser river. Major cities in the Leine catchment are Hannover, Goettingen, and Hildesheim. A map of Germany with the Weser catchment and the Leine area is shown in Fig. 3. The land area in the Leine catchment is predominantly used for agriculture and the main crops are winter cereals and sugarbeets. The topography varies between gently rolling and flat. Mean annual precipitation is about 665 mm and an estimated 25% of the generally deep loessial soils is tile-drained. North of Hannover, sandy soils are widespread.

During the past decades, the Leine area has repeatedly been struck by floods. The largest floods are usually observed in the humid wintertime, when rainfall of moderate intensity, but of large areal extent occurs, sometimes accompanied by snow melt. During the past 20 years floods along the Leine river were recorded in 3/81 and 12/81 (March and December 1981), 1/82, 1/86, 1/87, 3/88, 12/88, 3/90, 1/93, 1/94, and 3/94. The largest flood was the one in March 1981, with a recurrence interval of 30 years. During the wet month of March 1981, a combined rainstorm of 65 mm on four consecutive days triggered a major flood. For our present analysis we have therefore chosen this rainstorm as a sample case and have taken the design recharge rate (e.g. in Eq. (7)) as $R = 20$ mm d^{-1} for a 4-day period.

In our optimum drain spacing analysis for $R = 20$ mm d^{-1} for 4 days, we considered various values for the parameters H and D (Fig. 1), as well as for the hydraulic conductivity K. They were $D = 0.0$, 0.5, 1.0, 2.0, and 5.0 m and $K = 0.2$, 0.5, 1.0, and 2.0 m d^{-1}. For the drain depth we used mostly $H = 1.0$ m, but we considered also drain cases with an impervious barrier (Fig. 1) at the 0.9, 0.7, 0.5, and even at the 0.3 m soil depth. In these cases we assumed the tube (tile) or the mole drains to rest on the impervious boundary.

Also for the drainable porosity μ we used multiple values in our analysis. To facilitate the computations, a relation between μ and the hydraulic conductivity K was applied. Such an empirical relation bears some physical justification and has been repeatedly proposed in the literature (Eggelsmann, 1981; Chossat, 1987). The relation of Chossat and the relation $\mu = 0.1\sqrt{K}$, used, e.g. by Eggelsmann (1981) are shown in Fig. 4. In our analysis we decided to use the relation $\mu = 0.1\sqrt{K}$.

In our model, the parameter d (Fig. 1) plays an important role. Tabulated values for d (as a function of D, L, and r) can be found, for example, in van der Ploeg et al. (1999c). In our present study, with given values for L, we calculated d from the expression (van der Ploeg et al., 1999c):

$$d = \frac{L}{8\left[\frac{(L - \sqrt{2}D)^2}{8DL} + \frac{1}{\pi}\ln\frac{(1/2)\sqrt{2}D}{r}\right]}. \quad (15)$$

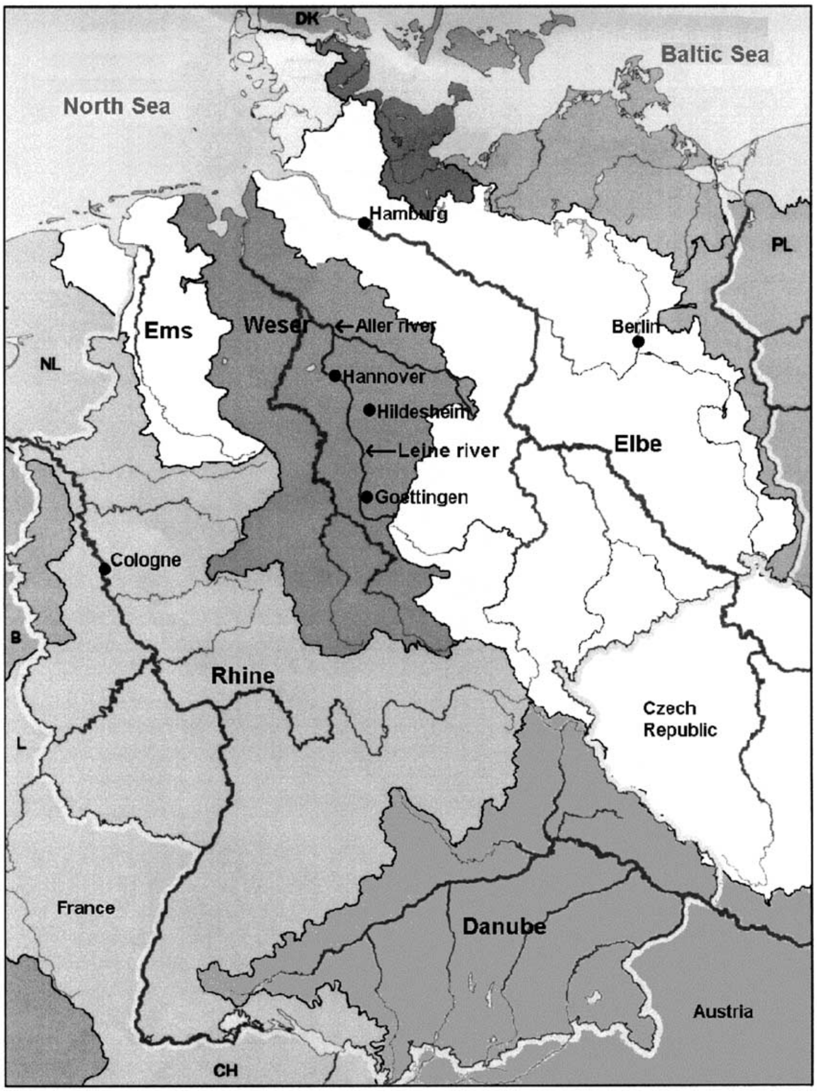

Fig. 3. The major river catchments in Germany, including the Weser catchment with Aller and Leine rivers and with the cities of Hannover, Hildesheim, and Goettingen.

To conclude this section, a remark about the parameter β of Eq. (14) seem to be appropriate. This parameter is a matching factor, without much physical significance. Its use in Eq. (14) influences however considerably the simulated rate of drain discharge, once the water table has reached the soil surface. To our knowledge, no experimentally determined β values for the case of a rising water table are available in the literature. The values that we assigned to β thus are rather arbitrary. It suffices here to say that we used values for β between 0.1 and 1.0. We will discuss the parameter β some more in Section 4. Finally, we remark that all our computations were performed with the program MAPLE of Waterloo Maple Inc. (1997).

4. Results and discussion

For a 4-day long rainstorm, with a rainfall intensity of $20\ \mathrm{mm\ d^{-1}}$ ($R = 0.02\ \mathrm{m\ d^{-1}}$), with tube (tile)

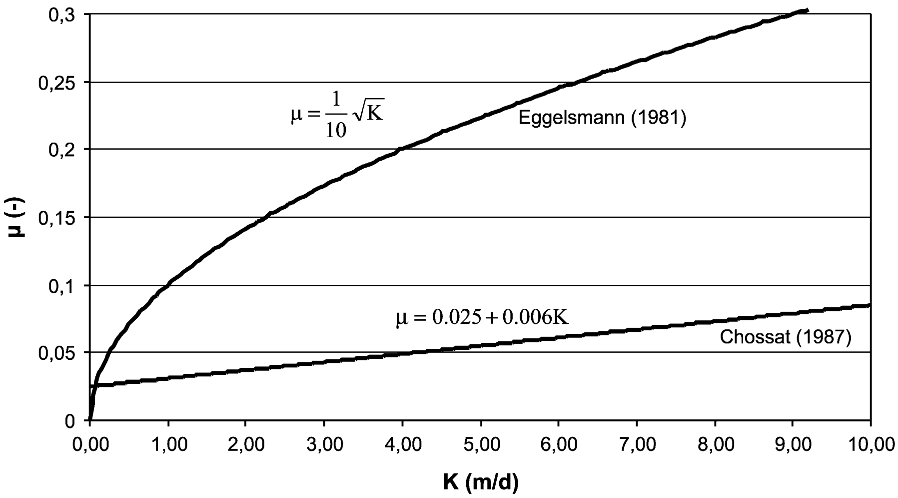

Fig. 4. The relationship between the soil hydraulic conductivity K and the drainable porosity μ, according to Eggelsmann (1981) and Chossat (1987).

drains at a depth $H = 1.0$ m, the optimum drain spacing L was calculated. It is the drain spacing L, at which the soil profile becomes completely saturated at the moment the rain stops. Hence, until then no surface runoff has occurred and the soil water retention at this moment reaches a maximum. We always started our computations assuming initially steady-state flow conditions to occur for a steady rainfall (recharge) rate of 1 mm d^{-1} ($R = 0.001$ m d^{-1}). Resulting values of L, for different values of D (Fig. 1) and for the hydraulic conductivity K, are shown in Table 1. For comparison also the drain spacings are shown (in parentheses) that are calculated with the conventional Hooghoudt equation (Eq. (1)), for a recharge design rate of 12 mm d^{-1}. The table shows, as expected, that the new values are considerably larger than the conventionally calculated values.

To show how much storage capacity is not made use of in case of the conventionally calculated drain spacings, the maximum water table height h_t (Fig. 2) and the average water table height h_{av} for the drain spacings listed in parentheses in Table 1, can be determined. The water table height h_t can be calculated with Eq. (8) (for $t = T$) and h_{av} with Eq. (6). For the drain spacing entries of Table 1, the corresponding h_{av} values (in cm) are listed in Table 2.

The table shows, for example, that for $K = 0.5 \times$ m d^{-1} and $D = 1.0$ m, $h_{av} = 46$ cm, which means that 54 cm of the soil profile is water-unsaturated. If the drainable porosity μ ($= 0.1K$) $= 7\%$, this means that 38 mm of water could have been stored additionally

Table 1
Optimum drain spacings for highest soil water retention in case of an extreme rainfall event; numbers in parentheses denote drain spacings calculated with the Hooghoudt equation (Eq. (1)) for $q = 12$ mm d^{-1}, $r = 0.1$ m, and $h = 0.5$ m

Hydraulic conductivity K (m d^{-1})	Depth D of the impervious barrier below the drains (m)				
	$D = 0.0$	$D = 0.5$	$D = 1.0$	$D = 2.0$	$D = 5.0$
	Drain spacing L (m)				
0.2	8.7 (4.1)	15 (7.0)	16 (8.2)	17.5 (9.3)	19 (9.5)
0.5	23 (6.5)	39 (11.1)	46 (13.5)	55 (16.1)	67 (18.2)
1.0	47 (9.1)	78 (15.7)	92 (19.5)	110 (24.0)	145 (29.4)
2.0	>91 (12.9)	>165 (22.2)	>190 (28.0)	>200 (35.3)	265 (46.0)

Table 2
The average height h_{av} of the water table above the level of the tile drains after 4 days of recharge ($R = 20$ mm d^{-1}), for drain spacings as calculated with the Hooghoudt equation (Eq. (1))

Hydraulic conductivity K (m d^{-1})	Depth D of the impervious barrier below the drains (m)				
	$D = 0.0$	$D = 0.5$	$D = 1.0$	$D = 2.0$	$D = 5.0$
	Average water table height, h_{av} (cm)				
0.2	51	51	50	51	53
0.5	49	47	46	45	45
1.0	46	41	40	38	38
2.0	40	34	33	32	32

for a drain spacing $L = 46$ m instead of $L = 13.5$ m (Table 1).

The use of β in Eq. (11) needs a comment. As mentioned earlier, no experimentally derived values for β for a rising water table seem to exist. Any assigned value to β is therefore arbitrary. Its effect on the rise of the drain discharge, after the water table has reached the soil surface, can be illustrated with the use of Fig. 5. For a flow configuration, as shown in Figs. 1 and 2, with $H = 1.0$ m, $h_{1,av} = 0.66$ m, and $h_{2,av} = 1.0$ m, the drain discharge q is shown as a function of h_{av} and of β. In view of field observations on drain discharge, we assumed that β is larger than 0.01, but smaller than 1.0. Simulations with HYDRUS-2D (Simunek et al., 1996) confirmed this assumption. Based on our experience, both in the field and with HYDRUS-2D, we therefore assigned a value of 0.5 to β ($\beta = 0.5$).

Because Eq. (14) does not have an analytical solution, the procedure discussed so far is somewhat cumbersome. The procedure can be simplified, if only a first approximation for the optimum drain spacing is required. This can be achieved with the Kirkham equation (Eq. (12)). Permitting soil saturation during a steady-state design recharge rate $R = q_2$, one can calculate the corresponding drain spacing L with Eq. (12). In Fig. 6 the relation between L and q_2 is shown for four different flow configurations ($H = 1.0$, $r = 0.10$, $K = 0.5$ m d^{-1}, and $Z = 1.0$, 1.5, 2.0, or 5.0, see Fig. 1). If, for example, a drain spacing is required,

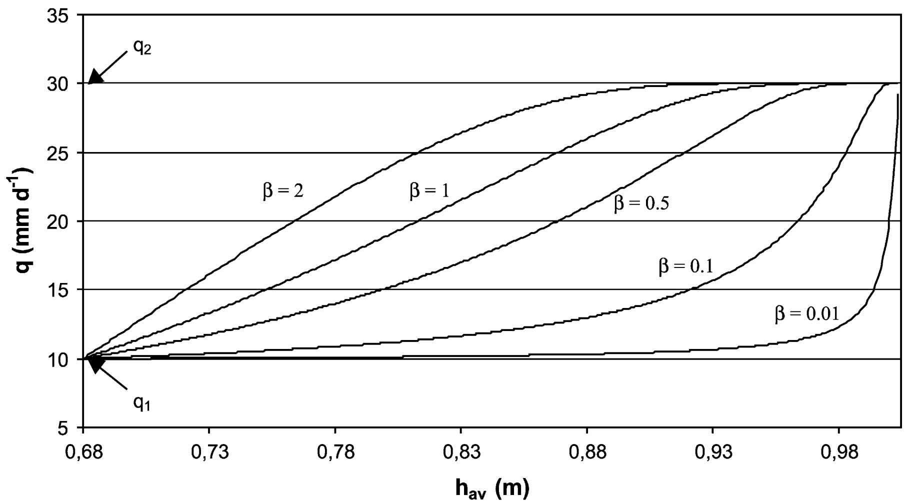

Fig. 5. The influence of the matching factor β of Salem and Skaggs (1998) on the calculated drain discharge q as a function of the average water table height h_{av}.

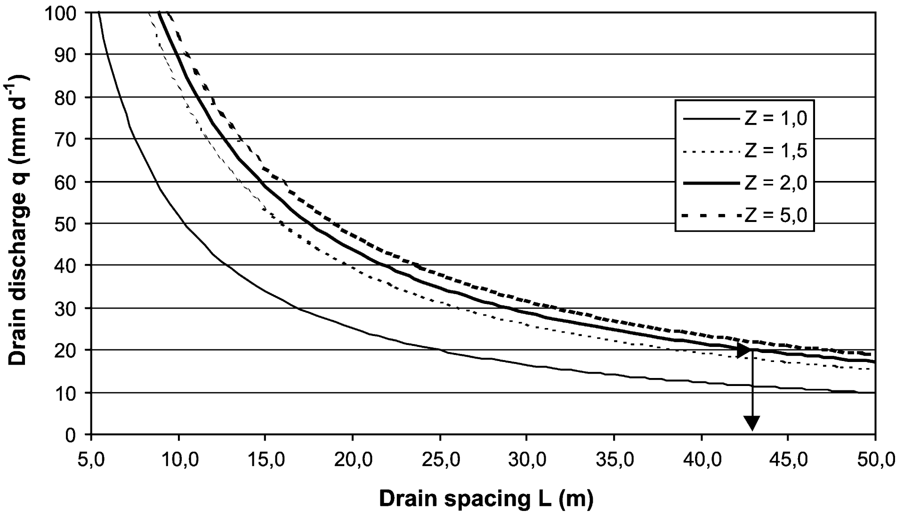

Fig. 6. The drain discharge q for the ponded water case of Kirkham (1957) as a function of the depth of the impervious boundary Z, for $K = 0.5$ m d^{-1}, $r = 0.1$ m, and $H = 1.0$ m.

such that at soil saturation a recharge rate R of 20 mm d^{-1} does not cause surface runoff (or ponded water), a drain discharge q_2 of also 20 mm d^{-1} is needed. If $Z = 2.0$ m (Fig. 1) this means that $L = 44$ m (Fig. 6). This number differs only slightly from the one given in Table 1 ($L = 46$ m), calculated with our newly proposed procedure. For other values of H, r, and K similar curves can be constructed.

The[1] presented non-steady drainage flow estimations assume that the drainage volume of the soil between the water table and the soil surface is characterize by a constant soil texture-dependent drainable porosity, an assumption common in groundwater hydrology. In theory, however, the drainage rate is a function of the rate of water table change and its proximity to the soil surface, thereby varying with time depending on drainage and redistribution rates. Nevertheless, the analytical approximations allow quantification of water flux across the water table as a result of changes in water table position, without solving the unsaturated water flow equation for the combined saturated–unsaturated soil domain. Alternatively, a full suite of numerical techniques is available that can solve for variably saturated flow with fluctuating water tables (Simunek et al., 1996; Skaggs, 1980) and that do not require restrictive assumptions as needed in the presented analytical solutions (e.g. constant drainable porosity and Dupuit assumption of dominantly horizontal water flow). These mechanistic numerical models will more accurately estimate drainage rates as a function of the unsaturated water flow dynamics between the water table and the soil surface. However, it is difficult to a priori assess the influence of the simplifying assumptions on optimum drainage spacing and storage capacity calculations. A comparison between semi-analytical and fully numerical solutions, as well as on extended analytical solutions, is ongoing.

[1] This paragraph was added by J.W. Hopmans and J. Simunek, because Dr R.R. van der Ploeg was unable to make requested revision due to illness.

5. Conclusions

In many countries subsurface drainage systems are designed with narrow spacing. With a narrowly designed drainage system it is achieved that in periods with excessive recharge the water table does not rise into the rooting zone of a growing crop and that the water table is falling quickly when the recharge stops. Because of the narrow design, the upper part of the soil profile therefore does not become saturated. It appears that because of such a design, drainage systems may add to river floods in periods with excess precipitation, especially when the system is practiced at a large scale, as in Germany. To increase soil water retention in wet periods, drainage design systems therefore may be reconsidered. We have shown that a modified drainage design system, that allows soil saturation, may increase soil water retention during periods with elevated recharge. The threat of river floods in such periods thus can be reduced, especially when the drain spacing is chosen not too small. With a larger drain spacing, the drainage performance of the system is admittedly lowered somewhat. However, as in the case of the Leine valley in Northern Germany, floods are usually observed during winter between December and March, when much arable land is bare or fallow. Under these circumstances, a high performance of the drainage system is not required. Restricted drainage efficiency under such conditions therefore may help to reduce the risk of winter floods.

How much loss of drainage efficiency can be expected, and which design rainstorm should be chosen, are questions that need to be answered regionally. The answers depend, among others, on the sensitivity to water logging and the worth of the cultivated crops, on the size of the land area that is drained, on the external costs caused by possible floods, and on the frequency of such floods. Restricted drainage efficiency is likely to affect crop yields. This, however, is not necessarily a disadvantage for a national economy. In Germany, for example, agriculture is heavily subsidized. As a consequence, there is an overproduction of such commodities as sugar, wheat, and barley. Because the costs of agricultural production are high, it is usually not possible to sell German agricultural commodities on the world market, unless also the export is subsidized. A reduced drainage efficiency thus seems advantageous both for the environment and the economy.

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References

Bouarfa, S., Zimmer, D., 1998. Water table shapes and drainflow rates calculation by Boussinesq's equation. In: Brown, L.C., (Ed.), Drainage in the 21st Century: Food Production and the Environment, Proceedings of the Seventh International Drainage Symposium, ASAE, St Joseph, MI, pp. 135–144.

Chossat, J.C., 1987. Relation between hydraulic conductivity and drainable porosity. Drainage Design and Management. Proceedings of the Fifth National Drainage Symposium. ASAE, St Joseph, MI, pp. 92–100.

Eggelsmann, R., 1981. Dränanleitung, Second ed, Parey Publishing Company, Hamburg.

Goudie, A., 2000. The Human Impact on the Natural Environment, Fifth ed, MIT Press, Cambridge, MA.

Hess, A., 1879. Meliorationen. In: Franzius, L., Sonne, E. (Eds.), Handbuch der Ingenieurwissenschaften. III. Band: Der Wasserbau, Verlag von Wilhelm Engelmann, Leipzig, pp. 622–711.

Kirkham, D., 1957. The theory of land drainage: the ponded water case. In: Luthin, J.N., (Ed.), Drainage of Agricultural Lands, Monograph No. 7, American Society of Agronomy, Madison, WI, pp. 139–181.

Krause, H., 1898. Über den Einfluß der Drainagen auf das Hochwasser der Flüsse. Der Kulturtechniker 1, 1–4.

Lesaffre, B., Zimmer, D., 1988. Subsurface drainage peak flows in shallow soil. J. Irrig. Drain. Div. ASCE 114 (IR 3), 387–406.

Luthin, J.N. (Ed.), 1957. Drainage of Agricultural Lands, Monograph No. 7, American Society of Agronomy, Madison, WI.

van der Ploeg, R.R., Sieker, F., 2000. Bodenwasserrückhalt zum Hochwasserschutz durch Extensivierung der Dränung landwirtschaftlich genutzter Flächen. Wasserwirtschaft 90 (1), 28–33.

van der Ploeg, R.R., Ehlers, W., Sieker, F., 1999a. Floods and other possible adverse environmental effects of meadowland area decline in former West Germany. Naturwissenschaften 86, 313–319.

van der Ploeg, R.R., Horton, R., Kirkham, D., 1999b. Steady flow to drains and wells. In: Skaggs, R.W., van Schilfgaarde, J. (Eds.), Agricultural Drainage, Agronomy Monograph No. 38, ASA/CSSA/SSSA, Madison, WI, pp. 213–263.

van der Ploeg, R.R., Kirkham, M.B., Marquardt, M., 1999c. The Colding equation for soil drainage: its origin, evolution, and use. Soil Sci. Soc. Am. J. 63, 33–39.

van der Ploeg, R.R., Czajka-Kaczka, A., Gieska, M., Akkermann, M., 2001a. Developments in agriculture and the loss of natural stormwater runoff control in Central Europe. In: Marsalek, J., Watt, E., Zeman, E., Sieker, H. (Eds.), Advances in Urban Stormwater and Agricultural Runoff Source Controls, NATO Science Series, IV. Earth and Environmental Sciences, vol. 6. Kluwer, Dordrecht, pp. 255–266.

van der Ploeg, R.R., Gieska, M., Schweigert, P., 2001b. Landschaftshydrologische und Hochwasser relevante Aspekte der ackerbaulichen Bodenbewirtschaftung in der deutschen Nachkriegszeit. Ber. Landwirtsch. 79 (3), 447–465.

Ritzema, H.P., 1994. Subsurface flow to drains. In: Ritzema, H.P., (Ed.), Drainage Principles and Applications, Inst. Land Reclam. Improv. (ILRI), Wageningen, pp. 263–304.

Robinson, M., 1990. Impact of improved land drainage on river flows. Report No. 113. Institute of Hydrology, Wallingford.

Robinson, M., Rycroft, D.W., 1999. The impact of drainage on streamflow. In: Skaggs, R.W., van Schilfgaarde, J. (Eds.), Agricultural Drainage, Agronomy Monograph No. 38, ASA/CSSA/SSSA, Madison, WI, pp. 767–800.

Salem, H.E., Skaggs, R.W., 1998. Predicting drainage rates under varying water table conditions. In: Brown, L.C., (Ed.), Drainage in the 21st Century: Food Production and the Environment, Proceedings of the 17th International Drainage Symposium, ASAE, St Joseph, MI, pp. 168–175.

van Schilfgaarde, J. (Ed.), 1974a. Drainage for Agriculture, Monograph No. 17, American Society of Agronomy, Madison, WI.

van Schilfgaarde, J., 1974b. Nonsteady flow to drains. In: van Schilfgaarde, J., (Ed.), Drainage for Agriculture, Monograph No. 17, American Society of Agronomy, Madison, WI, pp. 245–270.

Simunek, J., Sejna, M., van Genuchten, M.Th., 1996. HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media (manual). International Ground Water Modeling Center, Colorado School of Mines, Golden, CO, 167 p.

Skaggs, R.W., 1980. A water management model for artificially drained soils. N C Agric. Res. Serv. Tech. Bull. 267 North Carolina State University, Raleigh.

Skaggs, R.W., van Schilfgaarde, J. (Eds.), 1999. Agricultural drainage, Monograph No. 38, ASA/CSSA/SSSA, Madison, WI.

Waterloo Maple Inc., 1997. MAPLE V Release 5, Version 5.00. Waterloo Maple Inc., 57 Erb Street West Waterloo, Ontario N2L 6C2, Canada.

Zimmer, D., Lorre, E., Lesaffre, B., 1995. Parameter sensitivity and field evaluation of SIDRA model. Irrig. Drain. Syst. 9, 279–296.