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Computation Method of the Drainage Retention Capacity of Soil Layers with a Subsurface Pipe Drainage System

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Abstract

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Methodological procedure for determining the drainage retention capacity (DRC) of surface layers under conditions of unsteady-state groundwater flow was demonstrated. DRC of the drainage system can be defined as a groundwater reservoir situated between the soil surface and the intermediate position of a parabola shaped water table above the drain level. Computation of DRC is based on analytical approximation of the subsurface total drainage discharge in unsteady-state groundwater conditions. DRC formula can serve as a simple tool for immediate estimation that requires only minimum amount of basic information (drainage design parameters, soil hydrology data). DRC is an important phenomenon of drainage policy, an inseparable part of drainage processes, which can mitigate negative impact of climate dynamics. A properly applied drainage policy, with the possibility of manipulating the retention capacities in the soil layers, can significantly improve soil and environmental protection. In agriculture, DRC extended by a drainage system can mitigate the negative effects of hydrological extremes such as floods and droughts.

Keywords: agricultural areas; groundwater reservoir; hydrological extremes; unsteady-state groundwater conditions

One of many reasons of floods and water logging is a very low infiltration ability and especially unsatisfactory drainage capacity of surface layers in landscape (Deasy *et al.* 2014). Good infiltration and drainage conditions of surface layers in landscape cannot definitely eliminate floods, but can considerably mitigate their negative impacts (Hümann *et al.* 2011). The primary purpose of subsurface drainage systems is facilitation of agricultural production (Blann *et al.* 2009). Consequently, drainage outflow also results in the formation of retention space above the drainage system. The conception of the drainage retention capacity (DRC) is a new term, which represents hydrophysical characteristic of porous soil environment in a drainage hydrology area. DRC is directly dependent on drainage system parameters with a favourable effect on mitigating the negative impact of floods. The negative impact of extreme runoff, resulting in floods, can be reduced by taking the precautions (Kabat *et al.* 2004).

The present drainage study is aimed at establishing a methodological procedure leading to a direct computation of the retention capacity of surface layers under unsteady-state groundwater conditions. The method is based on a mathematical and physical description of the unsteady-state groundwater flow using the Boussinesq equation with an analytical solution.

Analytical solutions of unsteady-state groundwater flow are verified procedures that have been presented e.g. by Zavala *et al.* (2007); Fuentes *et al.* (2009), Singh (2009), and Dan *et al.* (2013).

The determination of DRC of surface layers with the use of subsurface pipe drainage systems is based on the analytical solution of subsurface total drainage quantity in a non-steady state drainage flow

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and in such a form it is being published for the first time herein.

MATERIAL AND METHODS

Fundamental principles, definitions, and equations. We assume a fully saturated soil profile with a high position of the water table level that is identical with the surface. For this soil profile, there is a subsurface pipe drainage system with drain spacing L (m), drain diameter r_0 (m), and drain depth h_d (m). The depth of the impervious floor below the level of the drain = 1 m (see Figure 1). Symbol h_0 (m) means the initial water table level (m) at time $t = 0$, and because the water table level is identical with the soil surface, the expression $h_0 = h_d$ is valid.

The water table level, drained by the subsurface pipe drainage system, begins to decrease from h_0 (m). In this case no recharge to the water table has been recorded and it means that the unsteady-state drainage flow principles can be applied.

DRC developed by operation of the subsurface pipe drainage system in unsteady-state groundwater conditions can be defined as a free gravity water drainable pore space under the surface. This drainable pore space, which does not contain any gravity water, is limited from above by the soil surface level and by parabola shaped water table situated above the drains from below (Figure 1). Determination of DRC is based on analytical approximation of subsurface total drainage quantity in unsteady-state groundwater conditions (Stibinger 2003). The solution coming from Boussinesq equation (1904) describes the unsteady-state saturated groundwater flow without any recharges to the water table:

$$HK\frac{\partial^2 h}{\partial x^2} = P\frac{\partial h}{\partial t} \tag{1}$$

where:

h – height of the water table level (m)

H – constant representing the average depth of the aquifer (m)

K – hydraulic conductivity (m/day)

P – drainable pore space, effective drainage porosity (–)

x – horizontal x-direction (x-coordinate) (m)

t – time (days)

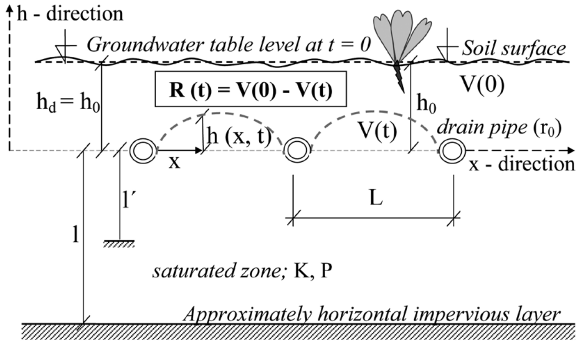

Figure 1. Height of the groundwater table h (x, t) at the distance $x > 0$ at the time $t > 0$, at saturated unsteady-state groundwater conditions and retention capacity of surface layers $R(t)$ at the time $t > 0$

The volume of the soil gravity water above the next two parallel drains at the time $t = 0$ can be expressed as

$$V(0) = h_d \times P \tag{2}$$

where:

$V(0)$ – volume of the soil gravity water above the level of the parallel horizontal subsurface drainage pipe system (at the time $t = 0$), expressed in m per unit surface area

Next step of the process will be clarified in the same way at the time $t > 0$.

The area above the next two parallel drains with drain spacing L (m) at the time $t > 0$ is approximately

$$\int_0^L h(x,t)dx \quad (\text{m}^2)$$

and in the same way as Eq. (2), Eq. (3) can be modified into:

$$V(t) = (P/L)\int_0^L h(x,t)dx \tag{3}$$

where:

$V(t)$ – volume of soil gravity water (water quantity) above the level of the parallel horizontal subsurface drainage pipe system (at the time $t > 0$), expressed in m per unit surface area

The expression

$$\int_0^L h(x,t)dx$$

can be modified into:

$$\int_0^L h(x,t)dx = \frac{8h_0 L}{\pi^2}e^{-at} = \frac{8h_d L}{\pi^2}e^{-at} \tag{4}$$

Parameter a represents drainage intensity factor

$$a = \frac{\pi^2 KH}{L^2 P} \quad (1/\text{day}) \tag{5}$$

By substituting the end of Eq. (4) into Eq. (3), we can define the formula for expressing $V(t)$ (m) and Eq. (3) can be written as:

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$$V(t) = \frac{8h_d P}{\pi^2} e^{-at} \qquad (6)$$

The retention capacity of soil layers $R(t)$ (m) created by the hydraulic function of the subsurface pipe drainage system at the time $t > 0$ and expressed in m per unit surface area is shown in Figure 1.

Retention capacity of soil layers $R(t)$ (m) is actually the released space under the surface. It is the difference between the volume of the soil gravity water $V(0)$ (m) at the time $t = 0$ and the volume of soil gravity water $V(t)$ (m) at the time $t > 0$, which can be expressed as:

$$R(t) = V(0) - V(t) \qquad (7)$$

After substitution of Eq. (2) and Eq. (6) into Eq. (7) and rearrangements, the equation for estimation of retention capacity of soil layers $R(t)$ (m) can be defined as:

$$R(t) = h_d P(1 - \frac{8}{\pi^2} e^{-at}) \qquad (8)$$

At this moment it is important to note, that the expression $h_0 = h_d$ is valid just for the case when position of the water table level is high and identical with the surface. But it means that the final formula (8) for approximation of the retention capacity of soil layers $R(t)$ (m) can also be written as:

$$R(t) = h_d P(1 - \frac{8}{\pi^2} e^{-at}) = h_0 P(1 - \frac{8}{\pi^2} e^{-at}) \qquad (9)$$

From the way of derivation of retention capacity of soil layers $R(t)$ (m), which leads to Eqs (8) and (9), and from the analysis and equations presented above, the expression for approximation of retention capacity of soil layers $R(t)_1$ (m) was extrapolated in a case where $h_d > h_0$ is valid. This equation can be expressed as:

$$R(t)_1 = P(h_d - h_0) + h_0 P(1 - \frac{8}{\pi^2} e^{-at}) \qquad (10)$$

After rearrangements Eq. (10) is as follows:

$$R(t)_1 = P(h_d - h_0 \frac{8}{\pi^2} e^{-at}) \qquad (11)$$

By approximation made in Eqs (8) and (11) with the knowledge of the basic subsurface drainage system parameters (L, r_0, h_d) and soil hydrology characteristics (K, P, h_0), it is possible to evaluate retention capacity of soil layers $R(t)$ (m) for a case where $h_0 = h_d$ is valid as well as $R(t)_1$ (m) for a case where $h_d > h_0$ is valid, at the time $t > 0$.

Dieleman and Trafford (1976) showed that all formulas and expressions derived from Boussinesq equation, which includes Eqs (8)–(11), are valid at a certain time, which was defined as:

$$\tau(\text{days}) = 0.4\,(-)/a\left(\frac{1}{\text{days}}\right) \qquad (12)$$

It should be kept in mind, that $R(t)$ (m) and $R(t)_1$ of the approximations (9) and (11) represent, from the physical point of view, a scalar. This means that volume, quantity, amount of drained space or mass is in this case expressed in length units (m).

RISWC experimental drainage field in Středočeská pahorkatina Upland (Czech Republic). Measured real values of the subsurface drainage discharges were obtained from the experimental field area, owned by the Research Institute for Soil and Water Conservation (RISWC) Prague-Zbraslav, Czech Republic (Soukup *et al.* 2000). From the geological point of view, the parent rock of the Cerhovice brook watershed area is formed of shale. All soil layers have low permeability, and the approximate depth of the impervious barrier is more than 1.0 m below the soil surface. The approximately 41.0 ha experimental field area is drained by a subsurface pipe drainage system. The thickness of the low permeable soil profile = 0.90 m, and the initial water table level $h_0 = 0.50$ m. The horizontal parallel systematic drainage system with drain spacing $L = 11$ m, average drain depth $h_d = 0.75$ m, and diameter of the lateral drain $r_0 = 0.06$ m is a typical shallow subsurface drainage system for heavy soils, with a low drainable pore space and hydraulic conductivity value $K = 0.075$ m/day, effective drainage porosity $P = 0.015$. The scheme of the drainage system parameters and soil conditions is shown in Figure 2.

The soil hydrology characteristics of the drained soil layers were measured in the terrain and verified

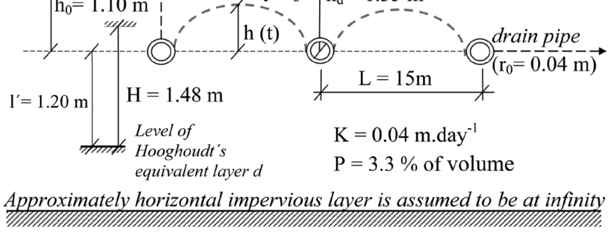

Figure 2. Drainage system parameters under unsteady-state groundwater conditions of the RISWC experimental drainage field in Prague-Zbraslav (Czech Republic)

doi: 10.17221/119/2013-SWR

in a laboratory (undisturbed core samples were used). The approximation of the hydraulic conductivity was carried out by the application of the single augerhole method, partially with the inversed single augerhole method and double ring infiltration method. The effective porosity was approximated from the soil water retention curves (Soukup *et al*. 2000).

The data used for the verification study were measured from June 2000 through July 2001. The measured subsurface drainage rate values were selected from the period May 4–17, 2001 after intensive precipitation (30 mm of recharge during May 4–6, 2001). During the drainage process, which was characterized by recession of the water table, no recharge to the water table level was recorded (e.g. through irrigation following rainfall, heavy rains or floods). The drainage process came to an end on May 29–30, 2001, when the drainage rate dropped below a value of 0.1 mm per day. The same data (Soukup *et al.* 2000) were used for approximation of subsurface drainage discharge by De Zeeuw-Hellinga theory (De Zeeuw & Hellinga 1958) and its verification (Štibinger 2009).

Experimental drainage field in the Mashtul Pilot Area (Nile Delta, Egypt). Historical data on the water table were obtained from Mashtul, situated in the Nile Delta. It was established in 1979–1980 as the Mashtul Pilot Area – Egyptian Dutch Advisory Panel (Ritzema 2009), where all variants of subsurface pipe drainage experiments in connection with crop production, soil salinity, depth of the water table, drain depth, and drain discharges for the south-eastern part of the Nile Delta were tested and verified.

The soil profile in this area can be presented as relatively homogeneous. The top clay layers are about 6 m thick, and a sandy aquifer forms the lower part of the soil profile. Low permeable (impervious), approximately horizontal layers are assumed to be at infinity. The average hydraulic conductivity value K is about 0.15 m/day for the eastern and central parts, where the data for the experiment were gathered. The continuous groundwater table level is deeper than 0.75 m below the surface. The climate of Mashtul is characterized by long dry summers and short winters, with a small amount of precipitation. The long-term annual average precipitation is 50–100 mm (Nijland *et al*. 2005; Ritzema 2007).

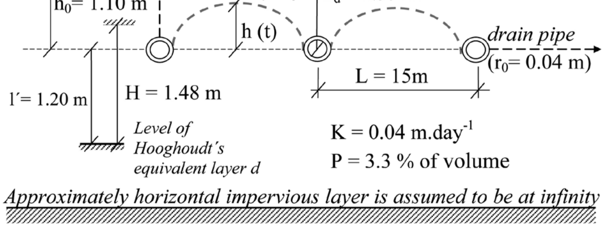

Figure 3. Subsurface pipe drainage system under unsteady-state groundwater conditions in the drainage unit of the Mashtul Pilot Area (Egypt)

The results of the soil investigation by Alterra-ILRI (2008) were used to estimate the representative hydraulic conductivity value for the drainage of the experimental field, K = 0.04 m/day and the drainable pore space value P = 3.3% of volume. The approximately horizontal impermeable layer is assumed to be at infinity. Drain spacing L = 15 m, drain radius r_0 = 0.04 m, and drain depth h_d = 1.35 m are the basic design parameters of the subsurface pipe drainage system, projected and selected in steady-state drainage flow, using the Hooghoudt equation (Hooghoudt 1940). The entire geometry of the subsurface pipe drainage system of the drainage unit in the Mashtul Pilot Area is shown in Figure 3.

RESULTS

RISWC experimental drainage field in Středočeská pahorkatina Upland (Czech Republic). The correctness of the results from the final Eqs (9)–(11) for calculations of the retention capacity of soil layers was verified using measured drainage discharge data and measured data for total subsurface drainage quantities from the RISWC experimental study area, Prague-Zbraslav.

The results of the initial hydraulic calculations from the drainage system show that the value of $l = l'$ = 0.15 m, because the lateral drains are situated very close to an impervious layer. The value of H equals to $l' + (h_0/4)$ = 0.275 (m) and indicates that the value of the drainage intensity factor a = 0.112 l/day. From the daily measured drainage rate values (mm/day) (shown in the third column of Table 1), the daily subsurface total drainage quantities were determined as well as the instantaneous retention capacity values of the soil layers (the fourth column of Table 1). The initial value for the retention capacity of the soil layers at the beginning of the drainage process, at the time t = 0, was approximated as $(h_d - h_0)\ P$ = 3.75 mm. In view of the fact that h_d = 0.75 m > h_0 = 0.50 m,

Table 1. Instantaneous and calculated values of the retention capacity of soil layers from the RISWC experimental field in Prague-Zbraslav (Czech Republic) and comparison of the differences between instantaneous and calculated values

Date	Time (days)	Drainage rate^1 (mm/day)	Retention capacity of soil layers^1	Retention capacity of soil layers^2	Differences^3	Differences (%)
			(mm)			
May 6, 2001	0	0.10	3.75	3.75	0.00	0.00
May 7, 2001	1	0.95	4.70	5.81	1.11	23.6
May 8, 2001	2	0.78	5.48	6.38	0.90	16.4
May 9, 2001	3	0.63	6.11	6.90	0.79	12.9
May 10, 2001	4	0.53	6.66	7.36	0.70	10.5
May 11, 2001	5	0.49	7.15	7.77	0.62	8.7
May 12, 2001	6	0.42	7.57	8.14	0.57	7.5
May 13, 2001	7	0.38	7.96	8.47	0.51	6.4
May 14, 2001	8	0.35	8.31	8.76	0.45	5.4
May 15, 2001	9	0.29	8.60	9.03	0.43	5.0
May 16, 2001	10	0.26	8.86	9.26	0.40	4.5
May 17, 2001	11	0.23	9.10	9.47	0.37	4.1

^{1}instantaneous values; ^{2}values calculated by Eq. (11); ^{3}absolute magnitude

which means that $h_d > h_0$, the daily retention capacities values for the soil layers (the fifth column of Table 1) were calculated using Eq. (11).

While the water table was receding through the subsurface pipe drainage system, no recharge (e.g. rainfalls, irrigations, heavy rains or floods) to the water table level was recorded (Soukup *et al.* 2000).

Experimental drainage field in the Mashtul Pilot Area (Nile Delta, Egypt). The correctness of the results produced by the final Eqs (9)–(11) for calculating the retention capacity of soil layers was also verified using historical measured data on the water table receding from an experimental drainage field in the Mashtul Pilot Area, situated in the Nile Delta in Egypt. The historical record of the water table fluctuation data from winter 1984 and from the beginning of 1985 were used (Ritzema 2009).

Shortly after irrigation, the highest water table of 0.25 m below ground level was recorded. As the drain depth $h_d = 1.35$ m, this means that $h_0 = 1.10$ m. During the drainage process, the water table $h(t)$ falls relatively slowly with time t, following the typi-

Table 2. Instantaneous and calculated values of the retention capacity of soil layers from the Masthul Pilot Area (Nile Delta, Egypt) and comparison of the differences between instantaneous and calculated values

Date	Time (days)	Water table^1 (m)	Retention capacity of soil layers^2	Retention capacity of soil layers^3	Differences^4	Differences (%)
			(mm)			
December 6, 1984	6	0.60	31.9	26.2	5.7	17.9
December 10, 1984	10	0.43	35.5	31.1	4.4	12.4
December 13, 1984	13	0.32	37.8	34.0	3.8	10.1
December 16, 1984	16	0.28	38.6	36.2	2.4	6.2
December 20, 1984	20	0.26	39.1	38.4	0.7	1.8
December 23, 1984	23	0.26	39.1	39.7	0.6	1.5
December 26, 1984	26	0.21	40.1	40.7	0.6	1.5
December 30, 1984	30	0.19	40.6	41.7	1.1	2.7
January 2, 1985	33	0.13	41.8	42.3	0.5	1.2

^{1}measured values; ^{2}instantaneous values; ^{3}values calculated by Eq. (11); ^{4}absolute magnitude cal exponential shape, and almost reaches the drain depth level. During the test period, no precipitation was recorded in the experimental drainage unit area. The process of subsurface unsteady-state flow into the drains was therefore not influenced by any recharge to the drainage water table.

Hooghoudt equivalent depth l' (m) of the soil layer below the level of the drain was approximated using the expression presented in Dieleman and Trafford (1976); Ritzema (2007) in a simplified form:

$$l' = \frac{l}{(8/\pi) \times (l/L) \times \ln(\frac{L}{\pi r_0}) + 1} \qquad (13)$$

As the impermeable layer l (m) converges to infinity ($l > L/2$), according to Dieleman and Trafford (1976) $l = L/2$ and for the value of Hooghoudt equivalent depth d (m) we can get $l' = 1.20$ m. If $H = l' + h_0/2 = 1.48$ m, then the drainage intensity factor $a = 0.0786$ l/day. The instantaneous values for the retention capacities of the soil layers were derived from time series of the recession of the water table level (the fourth column of Table 2).

Using Eq. (11) and from the known values of $h_0 = 1.1$ m, $h_d = 1.35$ m, and $a = 0.0786$ l/day and for a certain time t (day), the retention capacity values for the soil layers were calculated (the fifth column of Table 2).

DISCUSSION

The initial drainage measurements for estimating and analyzing the retention capacity of soil layers during the period of subsurface flow into the drains under unsteady-state conditions were started on May 7, 2001 ($t = 1$) and took place in the RISWC experimental area in Prague-Zbraslav. The saturated unsteady-state drainage flow from an experimental area of 41.0 ha was terminated on May 29, 2001, when the drainage discharge dropped below a value of 0.1 mm per day.

The comparison of the instantaneous daily values for the retention capacities of the soil layers and the retention capacity values for the soil layers calculated using Eq. (11) (see Table 1) clearly demonstrates that the shape of the curve for the instantaneous daily values and the shape of the curve for Eq. (11) are the same, with only some small differences.

The small differences between the instantaneous retention capacity values and the retention capacity values calculated using Eq. (11) are characterized by the high value of determination index $I_R = 0.970$. Table 1 shows clearly that the course of the time series of the differences (differences from the instantaneous retention capacity values for the soil layers minus $R(t)_1$, calculated using Eq. (11) is monotonous and slightly decreasing. This case serves as an example where the differences are inversely proportional to the retention capacity values for the surface layers. The higher the retention capacity value for the surface layers, the smaller the difference can be expected.

According to Dieleman & Trafford (1976), the validity of Eq. (11) is defined from the point of time $\tau = 3.57$ days (calculated using Eq. (12)). This means that from approximately May 10, 2001, the 4th day ($t = 4$) after the beginning of the drainage process, the analytical approximation expressed by Eq. (11) will be valid, and the corresponding difference on this day, at time $t = 4$ days, is 0.70 mm.

This is the greatest daily difference (approximately 0.70 mm, i.e. 10.5%) for the whole 41.0 ha of the experimental drainage area in this tested time series. Other differences are smaller.

The linearization of the Boussinesq equation, which forms the basis for the other derived formulas and equations, is more correct for deeper barriers. The case presented here is a typical example of a shallow soil drainage profile.

This approximation, where parameter H has been substituted by $l' + (h_0/4)$, introduces errors into the estimations of the drain flow discharges, and even larger errors for water table elevations, as utilized in the equations for the final expression of the retention capacity of the surface layers. The initially flat shape of the water table ($h(x, 0) = h_0$ at $t = 0$ for $0 \leq x \leq L$) can also explain why the calculated values are clearly greater than the measured and fitted values at the beginning of the tested period. At the end of the demonstrated period, which is presented in Table 1, the difference makes 0.37 mm (4.1%). The greatest daily difference that is valid in this period is 0.70 mm (10.5%).

The RISWC Prague-Zbraslav records show that at the end of the unsteady-state drainage process (May 29, 2001) the difference between measured and calculated values was only 0.26 mm. This fact fully confirms the hypothesis that higher retention capacity values for the surface layers lead to smaller differences (errors).

Finally, historical drainage data from 1984–1985 are presented (Table 2) as the initial basic data for calculating the retention capacity of the surface layers using Eq. (11). Eq. (11) is valid from a certain time

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point which was defined by Eq. (12). The data are from the experimental drainage field of the Egyptian-Dutch Advisory Panel on Land Drainage (Ritzema 2009). A comparison of the differences between the instantaneous and calculated retention capacity values for the soil layers in the Mashtul Pilot Area (Nile Delta, Egypt) is presented in Table 2.

It should be pointed out that the soil and drainage conditions in the Mashtul experimental drainage field are different from the conditions in the RISWC experimental field in Prague-Zbraslav. In the Mashtul experimental area, the drainable pore space value P is three times higher than in the RISWC experimental field, and the impervious barrier is also much deeper, tending towards infinity (Alterra-ILRI 2008; Stibinger 2011).

However, Table 2 shows results with the same characteristics both for the Mashtul and the RISWC experimental fields. It even seems that the calculated approximations used in Eq. (11) fit the instantaneous values closely, especially at the end of the test period. The suitability of the modelled formula represented by Eq. (10) is shown by the determination index with a high value of I_R = 0.956.

This means that Eq. (11) is also applicable in deeper drained soil profiles with more permeable soil conditions with higher porosity.

CONCLUSION

Based on the present results, Eq. (11) is seemingly a suitable tool for calculating the DRC of the surface layers developed by a subsurface pipe drainage system, approximating the real values.

Verifications of the simple analytical approximation of the retention capacity of the surface layers developed by a subsurface pipe drainage system calculated in Eq. (11) were carried out with data measured directly in the RISWC experimental field in Prague-Zbraslav, Czech Republic (Soukup *et al.* 2010) and in the experimental field in Mashtul, Egypt (Ritzema 2009).

The results presented here have shown good conformity between the computations and the measured data under unsteady-state drainage flow conditions in a deep soil profile with less permeable soil conditions.

The analytical approximation presented in Eq. (11) can be used as a simple tool for making an immediate estimate of the DRC value of soil layers developed by a subsurface drainage system, which can be further corrected or adjusted.

The equation should serve as a good and useful tool that requires only a minimal amount of information – basic soil hydrology data and basic design parameters of the drainage system. The verification of the field test results and measurements has shown that the equation can offer benefits to the user.

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