ISBN 978-93-84422-55-4
International Conference on Agriculture, Ecology and Biological Engineering (AEBE-15)
Antalya (Turkey) Sept. 7-8, 2015 pp. 1-7

Agricultural Land and Water Regime Protection by Drainage Retention Capacity (DREC) of Surface Soil Layers (Region of Cerhovice Brook, Czech Republic)

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Abstract**:** *Installing drainage systems in agricultural land with fully saturated soils decreases the level of the subsurface water table and enables the creation of groundwater reservoirs without gravity water – i.e. drainage retention capacity (DREC). DREC, which is created by the activity of a drainage system, can be defined as a groundwater reservoir limited by soil surface and by shape of the water table above the drains. By its infiltration capacity DREC can significantly mitigate negative impact of hydrological extremes, such as floods or heavy rainstorms. The purpose of this paper is, a) to present a methodology for direct determining DREC and b) to analyse the results of DREC application in agricultural land drainage system in the region of Cerhovice Brook (Czech Republic). The results obtained from in-situ experimental testing and numerical experiments confirmed that the equations presented in this paper can serve as a reliable tool for DREC approximation. Data collected in situ from the agricultural land drainage in Cerhovice Brook, confirmed that DREC can effectively improve agricultural land and water regime protection.*

Keywords: *Drainage retention capacity (DREC), drainage systems, groundwater flow to drains, analytical solution, agricultural land protection.*

1. Introduction

The main purpose of agricultural land drainage systems is to control the water table level in specific hydrological conditions, meeting the requirements of agriculturalists and other stakeholders. This implies the identification of the basic design parameters of agricultural drainage – drain spacing, drain diameter, drain depth – which affect (besides other things), the water table position and drain discharge, by discharging of groundwater excess.

Installing systems of drainage in saturated soils of agricultural landscape decreases the level of the water table and thus creates groundwater reservoirs (between the terrain surface and the water table above the drains) without any gravity water – drainage retention capacity (DREC).

DREC is an indication of the amount of water it can retain, e.g. part of the stormy rains, runoff developed floods, snow melting in early spring period, etc. DREC by its own infiltration and retention capacity has the potential to mitigate the negative consequences of extreme weather events in the form of hydrological extremes and can significantly decrease vulnerability of agricultural land a water regime.

In the period from 1997 to 2013 (16 years) there had been a total of 106 flood related casualties reported in the Czech Republic. From May 2010 to June 2013 (3 years), there had been 16 casualties reported in the Czech

Republic [8]. 15 % from the total area of the Czech Republic is agricultural land drainage surface. Optimising drainage capacity and infiltration conditions in the surface layers of agricultural land cannot completely resolve the problem of flooding. However, these measures can mitigate negative impact of flooding [4] and at the same time strengthen agricultural land as well as water regime protection.

The purpose of this paper is to describe the methodology and the formulas for direct calculation of DREC, under drainage design conditions. The derivation of final expressions is based on the balance of gravity water between soil surface and the drain level with reference to mathematical and physical descriptions of the non-steady state drainage flow, using the Boussinesq equation [1].

DREC is defined on the basis of analytical approximations of the shape of the water level above the drains in non-steady state drainage flow, in accordance with the Glover-Dumm formula and Dupuit's assumptions [3], [5] and [7]. Procedure of DREC determining was described and introduced during the Bioforsk NJF Drainage Seminar 602 in Sarpsborg (Norway) in August 2013 [8].

A slightly different approach was presented by Fuentes et al [2]. It is connected to DREC, and focuses on the soil-water retention curve and storage coefficient above the water level of subsurface pipe drainage systems. However, this approach does not demonstrate the explicit relationship between basic design parameters of subsurface pipe drainage system (drain spacing, drain depth, drain radius), soil hydrology parameters (hydraulic conductivity, drainable pore space), and DREC.

To validate the concept of DREC, the author used archive data (May 2001) collected from field measurements on heavy soils in the agricultural land of Cerhovice brook (Czech Republic), which serves also as experimental drainage area for the Research Institute for Soil and Water Conservation (RISWC) in Prague - Zbraslav [6],. The results of verification are presented in this paper.

2. Materials and Methods

2.1. Theoretical Review

DREC can be defined as a groundwater reservoir limited by soil surface and shape of the water level between two parallel neighbouring drains. Direct determination of DREC is based on balance of gravity water in soil profile and on approximation of subsurface water flow to drains based on analytical solution of linearized Boussinesq's Equation (1) with zero flow intensity above the free water level.

$$H.K\frac{\partial^2 h(x,t)}{\partial x^2} = P\frac{\partial h(x,t)}{\partial t} \tag{1}$$

where:

h (x,t) – height of the water table (M) above the level of the drain at distance x (M) (from the drain pipe) at time t (T)

H – average depth of the aquifer (M), H (M) can be approximated as $H = d + h_0/4$

d – equivalent impervious layer (M) of the soil below the level of the drains

h_0 – initial water table level (M) at time t = 0, midway between the drains

K – hydraulic conductivity ($M.T^{-1}$)

P – drainable pore space or effective porosity (-)

M – unit of length

http://dx.doi.org/10.17758/UR.U0915216

T – time unit

The parameter d (M) is the function of the drain spacing L (M), drain diameter r_0 (M) and D (M) which is the real depth of the impervious floor below the level of the drain [5a]. The next procedure is going to the direct determining of DREC.

a) parabolic shape of the initial water level

P-index marks the supposed fourth degree parabola shape of the initial water level above the drains at t = 0. The boundary conditions (0 < t, x = 0, x = L) for equation (1) are:

$$h_p(0,t) = h_p(L,t) = 0 \tag{2}$$

From the results of the United States Bureau of Reclamation [5b] can be approximated the shape of the initial water table as a fourth degree parabola and applied to the initial condition (0 < x < L, t = 0) for equation (1):

$$h_p(x,0) = \frac{8h_0}{L^4}(L^3x - 3L^2x^2 + 4Lx^3 - 2x^2) \tag{3}$$

Under the initial (2) and boundary (3) conditions and by the Tapp and Moody [7a] the lowering of an initially water level can be formed as:

$$h_p(x,t) = \frac{192h_0}{\pi^5}\sum_{n=1,3,5}^{\infty}\frac{n^2\pi^2 - 8}{n^5}e^{-n^2at}\sin\left(\frac{n\pi x}{L}\right) \tag{4}$$

where parameter a (T^{-1}) is drainage intensity factor, a = (π^2. K. H) / (L^2. P). In a next process the equation (4) is expressed as:

$$h_p(x,t) = 1.16h_0e^{-a.t}\sin\left(\frac{\pi.x}{L}\right) \tag{5}$$

Drainage retention capacity $DREC_p(t)$ (M) at an arbitrary time t > 0, expressed in the unit of length per unit surface area, with expected fourth degree parabola shape of initial water level (at t = 0) can be calculated by balanced equation:

$$DREC_p(t) = P.h_d - [P.1.\int_0^L h_p(x,t)dx]/[L.1] \tag{6}$$

where h_d (M) is drain depth. First term of the right part of equation (6), product $P.h_d$ (M), characterizes the groundwater reservoir between soil surface and drain level, second term represents the volume of water (water quantity) limited by drain level and parabola shape of water level above the drain (at time t > 0), expressed in the unit of length.

Balanced equation (6) after integrating can serve for direct calculation of drainage retention capacity $DREC_p(t)$ at an arbitrary time t > 0.

$$DREC_p(t) = P(h_d - \frac{2}{\pi}1.16h_0e^{-at}) \tag{7}$$

With use of modified equation (5), formula (7) can be expressed as:

$$DREC_p(t) = P\left[h_d - \frac{2}{\pi}h_p(t)\right] \tag{8}$$

where $h_p(t)$ is water level above the drains at t > 0 midway between the drains, supposing fourth degree parabola shape of the initial water level. Graphical scheme of the $DREC_p(t)$ approximation, $h_p(t)$ and a shape of the water level $h_p(x,t)$ in a case of parabolic initial water table represents Figure 1.

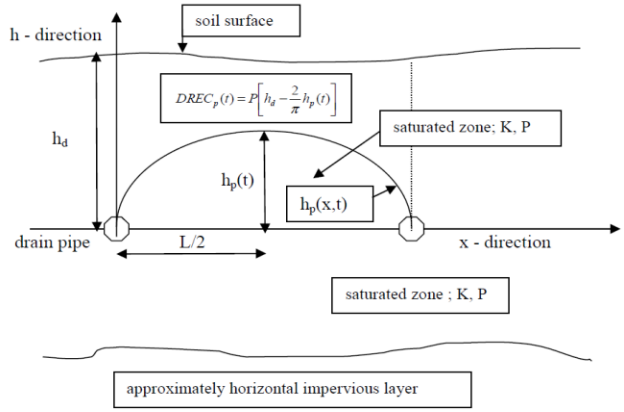

Fig. 1: $DREC_p(t)$ and shape of the water level $h_p(x,t)$ at distance x > 0 at time t > 0 supposing the parabola shape of initial water level.

b) horizontal initial water level

In the case of the approximately horizontal initial water level the procedure of derivation of formula to direct determining DREC at time t > t is the same. The boundary conditions (0 < t, x = 0, x = L) for analytical solution of equation (1) are:

$$h(0,t) = h(L,t) = 0 \tag{9}$$

Supposed shape of the initial water table is approximately horizontal and the initial condition (0 < x < L, t = 0) for equation (1) can be expressed as:

$$h(x,0) = h_0 \tag{10}$$

Analytical solution of equation (1) under the initial (13) and boundary (14) conditions presented Dumm and Glover [5b] and for the lowering of an initially horizontal water table level h_0 (M) shaped:

$$h(x,t) = \frac{4h_0}{\pi} \sum_{n=1,3,5}^{\infty} \frac{1}{n} e^{-n^2 at} \sin(\frac{n\pi x}{L}) \tag{11}$$

Equation (11) can be expressed as:

$$h(x,t) = \frac{4h_0}{\pi} e^{-a.t} \sin(\frac{\pi.x}{L}) \tag{12}$$

Next process leading to the direct calculation of the drainage retention capacity DREC(t) (M) in an arbitrary time t (t >0) is identical with the previous case. DREC(t) expressed in the unit of length per unit surface area can be determined as:

$$DREC(t) = P(h_d - \frac{8}{\pi^2} h_0 e^{-at}) \tag{13}$$

or with use of modified equation (12) expression (13) can be written as:

$$DREC(t) = P\left[h_d - \frac{2}{\pi} h(t)\right] \tag{14}$$

Where h(t) is water level above the drains at t > 0 midway between the drains, supposing the horizontal initial water level. By approximation, expressed in the equations (7), (8), (13) and (14) with basic design parameters of drainage system (L, r_0, h_d) and soil hydrology data (K, P, h_0) can be determined the value of DREC in certain time t > 0.

An approximation of DREC at time t > 0 by the height of the water table midway between the drains, i.e. by equations (8) and (14), enables to estimate DREC concept in the transient (non steady-state) as well as steady-state drainage flow conditions. It means that the concept of DREC is applicable in any type of drainage flow.

2.2. Study Area - Agricultural Land of Cerhovice Brook Region

In order to verify the soundness of the DREC concept and to validate the equations used for DREC computation, the archive data from field measurements (realised in May 2001) in the heavy soils of the agricultural land of Cerhovice Brook, were used. This locality of 40.5 hectare serves also as an experimental drainage area of RISWC Prague-Zbraslav and is situated in the Central Czech Uplands with an altitude of 350–500 meters above sea level. The total watershed surface area has around 7.3 square kilometres.

Data from the period between May 4 and May 30, 2001, after relatively intensive precipitation (30 mm of recharge during of the May 4 – May 6, 2001), were used for verification purposes. During the period from May 7 to May 30, 2001, no recharge was recorded to the water table level of the pipe drainage system (e.g. from subsequent rainfalls, irrigation runoff, heavy rains or floods). The cessation of the non-steady state drainage flow occurred between May 29 – May 30, 2001, when the drainage discharge decreased under the value of 0.09 mm per day. The research experimental area is drained by a subsurface pipe drainage system with the drain spacing L = 11 m, average of the drain depth h_d = 0.75 m and diameter of the lateral drains r_0 = 0.06 m.

This case represents a typical example of the shallow subsurface drainage system of heavy soils with its low hydraulic conductivity K = 0.075 m.day^{-1}, drainable porosity P = 0.015 (-) and low permeable soil profile of thickness 0.90 m. The initial position of the water table level h_0 = 0.5 m, at the beginning of tested period, was approximated from the records of the water levels in piezometers. Equivalent impervious layer d (M) is identical with position of real impervious layer bellow drains, d = 0.15 m. Average depth of the aquifer H (M) can be approximated as H = d + h_0/4 = 0.275 m, drainage intensity factor a (day^{-1}) = (π^2. K. H) / (L^2. P_d) = 0.112 day^{-1}.

DREC was measured through the subsurface total drainage quantities. The subsurface drain discharges were measured by ninety-degree triangular noth weir. A plastic float situated behind this weir is placed in to the reservoir, which is connected to an automatic level recorder. The course of the drainage discharges in time t was estimated from the water-stage recording chart. The daily values of the subsurface total drainage quantity, as well as the DREC (mm), were generated from measurements of the mass-drainage rate curve.

2.3. Results and Discussions

The results from field experimental testing (from period between May 4 and May 30, 2001) for verification of concept of DREC and for verification of correctness of equations going to DREC approximation, are seen in TABLE I.

TABLE I: Measured and calculated daily values of DREC from location of Cerhovice Brook, RISWC Prague-Zbraslav experimental drainage area (May 2001)

Day	DREC (mm) measured values	DRECp(t) (mm) - calculated by equation 7 - parabolic initial water table	DREC(t) (mm) - calculated by equation 13 - horizontal initial water table	Absolute magnitude of differences (mm), DREC - DRECp(t)	Absolute magnitude of differences (mm), DREC - DREC(t)
1 May 7	4.7	6.3	5.8	1.6	1.1
2	5.48	6.82	6.38	1.34	0.9
3	6.11	7.29	6.9	1.18	0.79
4	6.65	7.71	7.36	1.06	0.71
5	7.15	8.08	7.77	0.93	0.62
6	7.57	8.42	8.14	0.85	0.57
7	7.93	8.72	8.47	0.79	0.54
8	8.31	8.98	8.76	0.67	0.45
9	8.60	9.23	9.03	0.63	0.43
10	8.86	9.44	9.26	0.58	0.4
11 May 17	9.10	9.63	9.47	0.53	0.37
18 May 24	10.43	10.51	10.44	0.08	0.01
23 May 29	11.05	10.82	10.78	0.23	0.27

Measured DREC data, and calculated values of DREC with parabolic /$DREC_p(t)$/ and horizontal /DREC(t)/ shape of the initial water level (see TABLE I), are quite consistent. If we compare the values of $DREC_p(t)$ and DREC(t) with measured data of DREC (into TABLE I), it is obvious that the trend of all the curves is almost identical, even though some differences are apparent. However, compared to the measured values of DREC, these differences are very small (less than 1.6 mm), and with reference to large tested drainage experimental area of 40.5 hectare, they can be considered as negligible.

The parametric T-test did not reject null hypothesis H_0: that there is no differences between measured values of DREC and calculated values of DREC by equation (7) and (13). If this null hypothesis H_0 is rejected, the probability of error would fluctuate from 20% to 40%, and this is not acceptable. In fact, the differences between DREC values derived with parabolic initial water table, and DREC values determined supposing the horizontal initial water level, are insignificant.

The high values of correlation coefficients between measured data and calculated values of DREC (converge to 1.0) and the results of the analysis of statistical indicators have shown, that equation (7) and (8), as well as (13) and (14), are a good tool for approximation of DREC.

From the data shown in TABLE I it follows that, for example, after 7 days of drainage process the value of DREC is about 8 mm, which represents (in a case of an agricultural land area of 40.5 hectares) 3240 m^3 of water. This is not a negligible amount of water. This water can effectively be retained by the DREC potential, created by the activity of an agricultural land drainage system. At the end of the drainage process this can amount to 4455.00 m^3 of water. The fact that the DREC can be of great value in drainage hydrology, and can significantly contribute to the agricultural land and water regime protection, should not be neglected.

2.4. Conclusions

The methodology for determining DREC is based on an analytical solution of the partial differential equations for unsteady drainage flow. The process leads to the explicit expressions of DREC estimation. Final formulas can be used as a simple tool for immediate DREC assessment. Such procedure is very useful for DREC approximation, requiring only a minimum amount of fundamental information, i.e. basic soil hydrology data and parameters of the drainage system.

Detailed investigation of the DREC concept in steady-state approach is currently being carried out at CULS Prague, Faculty of Environmental Sciences, Department of Land Use and Improvement, in the framework of a drainage research project, financed by the Ministry of Agriculture of the Czech Republic. Partial results of the research have confirmed that in the process of determining DREC, the Hooghoudt Equation for steady-state flow can be used. This in turn can be useful for designing drainage system parameters, with estimation of DREC effect in any type of drainage flow.

Drainage systems with high DREC capacity can significantly reduce negative impact of hydrological extremes, e.g. floods and waterlogging, especially with reference to the current and future climate dynamics conditions. DREC is an important innovation in the field of drainage hydrology. As an integral part of a drainage system, DREC can significantly contribute to agricultural land and water regime protection.

3. Acknowledgements

This work was supported by the Ministry of Agriculture of the Czech Republic (NAZV), through the Grant No. QJ 122 0050.

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