TERRAIN EXPERIMENTAL MEASUREMENT OF SATURATED HYDRAULIC CONDUCTIVITY ON PADDY FIELDS IN TAOYUAN (TAIWAN) DURING THE CYCLE OF FLOODED PERIOD

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Abstract

The saturated hydraulic conductivity is one of the most important indicators in the irrigation and drainage policy of water management of paddy fields and for its determination only direct measurement should be used. Indirect methods, which are derived from the soil textural characteristics, don't need to give truly values. Simple field method of determination of the saturated hydraulic conductivity of surface soil layers on paddy fields, during the cycle of flooded period, by direct terrain experimental measurements with help of single ring infiltrometr is viewed in this paper. By this method were measured saturated hydraulic conductivities on Taoyuan's paddy fields in Taipei (Taiwan) during the cycle of flooded period. The results, obtained by this terrain experimental method, with use of the nonlinear regression, actually with help of the Marquardt search algorithm were successfully compared with the results of laboratory measurements on the "undisturbed" core samples.

Key words: Saturated hydraulic conductivity, paddy fields, water table, terrain experimental measurements, ring infiltrometer, Darcy's law, time series analysis

INTRODUCTION

Saturated hydraulic conductivity is one of the principal soil hydrology characteristics, especially in a case of soils of paddy fields. At the same time, saturated hydraulic conductivity is one of the most important factors in water management design of paddy fields, while it is indispensable for the control of paddy field water regime. In this case, soil layers on paddy fields in Taiwan, measured directly on the fields during the cycle of the flooded period, were used to determine the saturated hydraulic conductivity of the surface. Indirect methods, which use the soil's textural characteristics, don't necessarily provide true values.

Saturated hydraulic conductivity is expressed by units of velocity (M/T), where symbol M is unit of length and symbol T is time unit. The definition of the saturated hydraulic conductivity follows from the Darcy's Law (Darcy, 1856; Kutílek and Nielsen; 1994). In the saturated flow conditions the velocity of water flow v (M/T) in the soils or in the other porous media, is directly proportional to the slope of water table I (–).

The coefficient of this direct proportionality is a constant with units of velocity (M/T), usually is marked by symbol K (M/T) and is named saturated hydraulic conductivity. The relates, described above, can be generally expressed by equation (1)

$$v = K \times I \qquad (1)$$

Saturated hydraulic conductivity K (M/T) can characterize the hydraulic properties of soils, earths and also the hydraulic properties of the other porous materials and media, from the point of view of the velocity of water flow in their porous fully saturated flow conditions. The values of the saturated hydraulic conductivities K (M/T) of some selected soils and rocks are presented in Table 1 (Todd and Mayes, 2005).

The value of saturated hydraulic conductivity K (M/T) of the surface layers of paddy fields should be relatively small to minimize the seepage losses. But the soils of surface layers of paddy fields should not be definitely impermeable, because it is better if after the flooded period, when the surface waters flayed off from the surface, the water regime of paddy fields can be under the control of the horizontal pipe drainage systems.

The typical picture of the most of the Vietnamese paddy fields from Mekong delta and from basins of Red River is a presence of the very low permeable thin layer with saturated hydraulic conductivity perhaps less than 1×10^{-6} m/s, placed approximately 60 or 70 cm under the surface of paddy field. Soils surface layers of fluvial deposits above this low permeable layer will be much more permeable (Nguyen, 2007).

Egyptian paddy fields in Sakha (Rycrroft and Mohamed, 1995), situated in the northern part of the

Tab. 1: Hydraulic saturated conductivities K (m/s) of selected soils and rocks (Todd and Mayes, 2005)

Earth, soil, material	Hydraulic saturated conductivity K (m/s)
Clay, heavy soils	2.0×10^{-9}
Gravel, medium	3×10^{-3}
Peat	6.6×10^{-5}
Dune sand	2.3×10^{-4}
Dolomite	1×10^{-8}

Nile delta, dispose of un-drained heavy textured saline-sodic soils of clay, composed mainly montmorillonite, with some kaolinite and illite, with saturated hydraulic conductivity about 1.4×10^{-6} m/s.

Another Egyptian paddy fields, located in Mashtul (ILRI, 2008), in the south eastern part of the Nile delta, consists of soils with clay cap, which contains dark brown stiff clay, without cracks the saturated hydraulic conductivity is about 9.3×10^{-7} m/s.

Saturated hydraulic conductivities of the soil surface layers of paddy fields in Taoyuan (Taiwan), were measured on selected experimental area during the cycle of flooded period by the direct field experimental measurements, with use the of individual single ring infiltrometers (Kutílek and Nielsen, 1994).

MATERIALS AND METHODS

Study area

In Photo 1 is viewed a suburb of Taipei (Taiwan) which is characterized, besides others, by the big amount of greater and smaller paddy fields. They are situated even in the very urbanized parts of the sub-cities. The experimental paddy field area 10 m × 10 m with single ring infiltrometer, which is shown in Photo 2, was selected from the paddy fields, placed in the Taipei's suburbs.

The locality of interest approximately from 4 to 6 hectares, with an experimental paddy field area, is situated in Taoyuan (suburb of Taipei), very close to the main street Chungshan Road, around 50 minutes by subway from the world's highest skyscraper "101" (Stibinger, 2001).

The landscape in the place of experimental paddy field area and in the close neighbourhood is almost flat. The altitude of this place is approximately a few tens of meters above the sea level. The climate is warm and humid, with the annual average temperature about 21°C. The monthly average temperature is 15°C in January and 28°C in July. The total annual precipitation amounts to 2 450 mm, with more rainfall in monsoon season between mid May and mid June and in typhoon season between July and September.

The study was performed at the paddy field area on the Anthrosois, which were fine-texture. They have been formed on the alluvial deposit of the local no-named small streams. Permeabilities of soil layers varied from low to average values. The impervious barrier was approximately from three to four meters below the soil surface. The studied top-layer was fine-texture, homogenous and isotropic.

Photo 1: Typical picture of paddy field situated on the suburb of Taipei (Chungshan Road, Taoyuan, Taiwan, photo J. Stibinger)

Photo 2: Experimental area for measurement of saturated hydraulic conductivity, placed on the paddy field of the Taipei's suburb (Taoyuan, Taiwan, photo J. Stibinger)

Theoretical

In Figure 1 is shown single ring infiltrometer of the experimental paddy field in the one-dimensional system with vertical y-direction, positive upward, and horizontal referential level, which is identical with water table level on the surface of experimental paddy field.
By an addition of the certain amount of water into the single ring infiltrometer, the water table level inside the infiltrometer goes up to the level H0 (M), which represents water table level (M) in infiltrometer at the beginning of measurement, at time t = 0. By gravity the water level in infiltrometer gradually goes down from the level H0 to the level y1, y2, etc., finally to y = 0, from the time t = 0 to the corresponding times t1, t2, etc., finally tn. Nevertheless it is valid H0 > y1 > y2 > 0 and 0 < t1 < t2 < tn (see Figure 1).
In saturated flow conditions and according to Darcy's law the flow velocity v_s (M/T) in the soil sample of experimental infiltrometer in the vertical y-direction can be approximated as:

$$v_s = -K \frac{y}{2L} \quad (2)$$

where L (M) represents the depth of the infiltrometer under the soil surface of experimental paddy field. The value of 2L (M) characterizes the approximation of the supposed trajectory of the water particles in the terrain tested soil sample of paddy field. Negative sign in a right part of equation (2) marks the flow, which is running down, it means opposite to the positive direction of y-axis.
The flow velocity v_i (M/T) in the infiltrometer can be expressed as:

$$v_i = \frac{\partial y}{\partial t} \quad (3)$$

It is supposed that the flow velocity v_s (M/T) in the soil sample of experimental infiltrometer in y-direction will be equal as the flow velocity v_i (M/T) in the infiltrometer ($v_s \equiv v_i$) and we obtain:

$$-K \frac{y}{2L} = \frac{\partial y}{\partial t} \quad (4)$$

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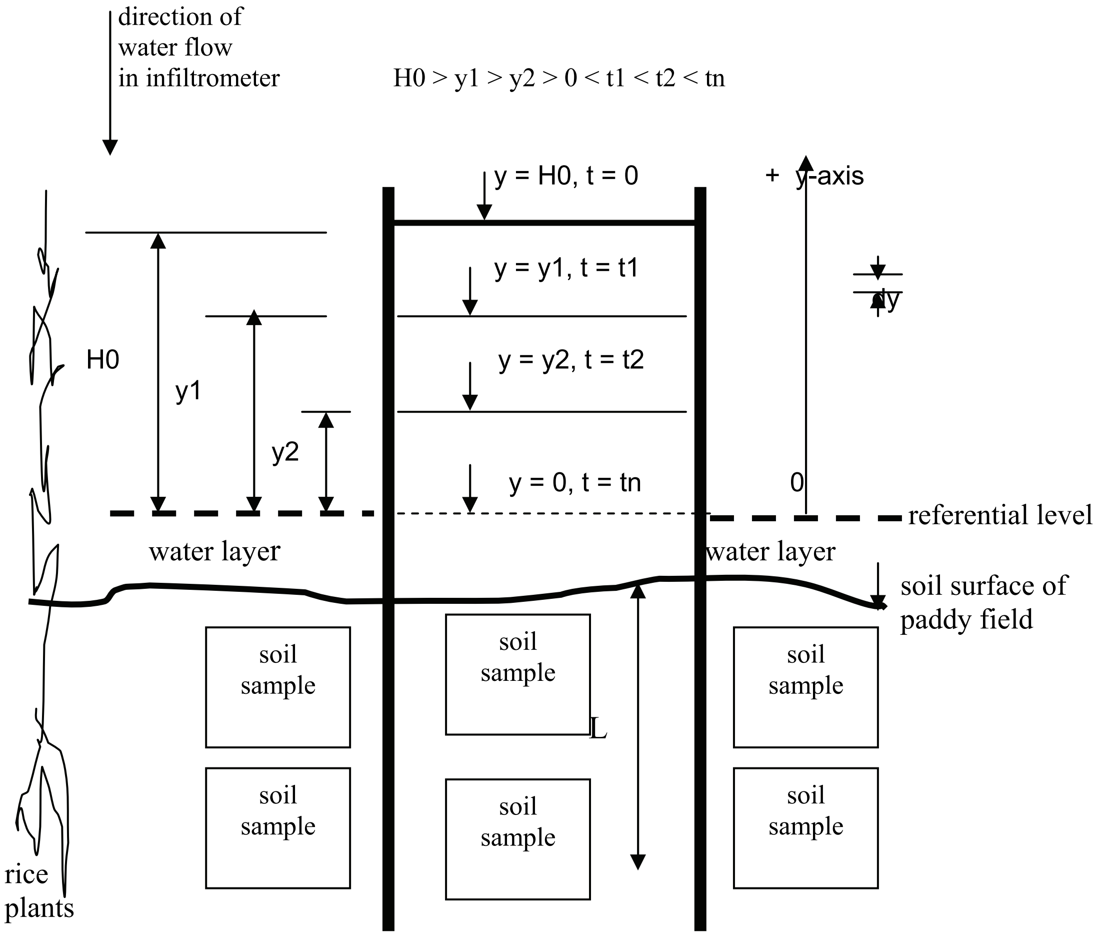
Figure 1. Process of decreasing of water table level in the single ring infiltrometer in an experimental area of paddy field



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$$-K\frac{y}{2L} = \frac{\partial y}{\partial t} \qquad (4)$$

From rearrangement equation (4) we get ordinary differential equation, which can be formed as:

$$\partial t = (\frac{-K}{2L}).y^{-1}\partial y \qquad (5)$$

Let's suppose, that the decreasing of water table level in infiltrometer will be e.g. from level y1 (M) to level y2 (M). The corresponding times are t1 (T) and t2 (T). Integration of equation (5) can be expressed as:

$$\int_{t1}^{t2} dt = (\frac{-K}{2L})\int_{y1}^{y2} y^{-1}dy \qquad (6)$$

After integration from y1 to y2 in y-axis direction and from t1 to t2 in time axis and after other corrections we get:

$$\frac{y1}{y2} = \exp\left(\frac{K}{2L}[t2 - t1]\right) \qquad (7)$$

Formula (7) can be expressed as integral curve by vector Y, vector X, parameter P1 and constant H0 as:

$$Y(y1, y2.....yi.....yn) = \frac{H0}{\exp[P1.X(t1, t2.....ti.....tn)]} \qquad (8)$$

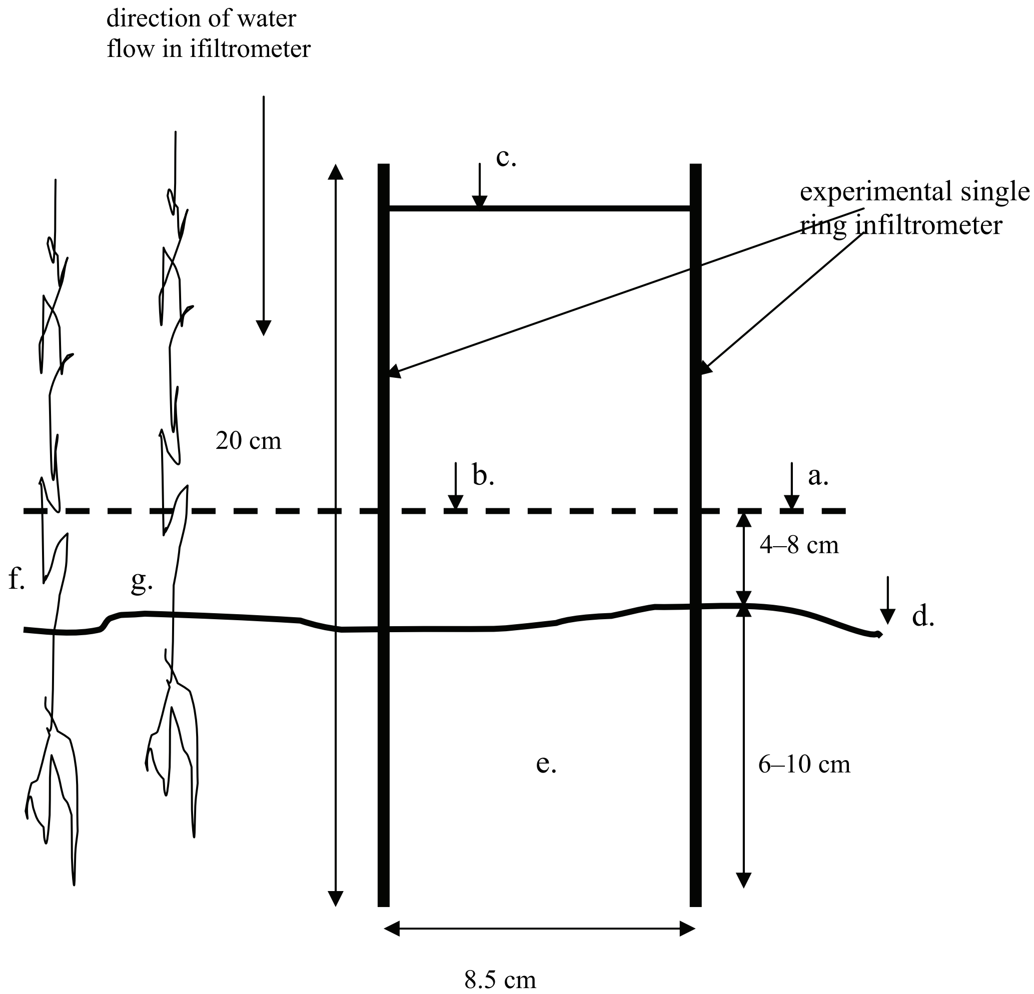
P1 is a function of hydraulic saturated conductivity K (M/T) and supposed trajectory of the water particles 2L (M) in the terrain tested soil sample of paddy field. Parameter P1 can be expressed as P1 = K/2L (/T). H0 represents the water table level (M) in infiltrometer at time t = 0. The vector Y(y1, y2…..yi……yn) represents

dependant variables and vector X(t1, t2…..ti,….tn) represents independent variables.
By nonlinear regression analysis of the equation (8) can be determined parameter P1 (/T). Then from the known approximated value of 2L (M) is possible to calculate the value of hydraulic saturated conductivity K (M/T) in the terrain tested soil samples of experimental area of paddy field by expression P1 (/T) = K/2L, respectively K (M/T) = P1.2L.
The vector Y(y1, y2…..yi……yn), vector X(t1, t2…..ti….tn), constant H0 and the shape of the equation (8) are known values (information), unknown value of P1 will be calculated by nonlinear regression, with use the method of Marquardt (Marquardt, 1963), known also as the method of Marquardt and Levenberg. The estimation of the value of P1, that fit the data best, is the goal of the nonlinear regression processing (GraphPad Software Inc., 2001).

RESULTS – MEASURED AND CALCULATED VALUES

Terrain experiments on the experimental area of paddy field were made during the cycle of flooded period, what means after the rice planting, which was realized after irrigation of paddy field. During terrain experimental measurement of saturated hydraulic conductivities, was the surface of the experimental paddy field permanently under the water table. The thickness of water layer above the surface of experimental paddy field fluctuated approximately from

Figure 2. Scheme of single ring infiltrometer stepped at an experimental area of paddy field in Taoyuan (Taipei, Taiwan)



Legend:
a. water table level (w.t.l.) on the experimental paddy field, outside of infiltrometer
b. w.t.l. inside of infiltrometer before of addition of water
c. w.t.l. inside of infiltrometer after of addition of water
d. surface of soil layers of experimental paddy field
e. soil sample of experimental paddy field
f., g. rice plants planted after irrigation and before experimental measurement

5 cm to 8 cm. For one's own measurement of saturated hydraulic conductivity was used single ring infiltrometers. A few centimeters (from 6 cm to 10 cm) under the surface of soil layers of the experimental area of paddy field were vertically pressed down single ring infiltrometers of heights 20 cm, with inside diameters 8.5 cm. Scheme of the single ring infiltrometer stepped at the experimental paddy field views Figure 2.

By this way, with help of the single ring infiltrometers, were formed individual samples of soil in paddy fields, on which were measured, directly in the terrain, the data wanting for estimation of the saturated hydraulic conductivities. At the beginning of measurement is the height of the water layer above the surface of the area of paddy field (outside of infiltrometers) the same as the height of the water layer inside of the infiltrometers. Usually it is a few centimeters of water (e.g. from 4 cm to 8 cm), which is necessary to keep above the surface of paddy field during the flooded period.

By an addition of the certain amount of water into the infiltrometers, the water table level inside the infiltrometers increases to the level H0 (cm). Falling water heads inside of infiltrometers, developed by gravity, in time t = 0 from level H0 (cm) gradually to the y1 (cm), y2 (cm) etc. (see Figure 1) are measured by the millimeter's scale and recorded as the time series of decreasing of water table levels inside of individual infiltrometers.

A representative example of the record of the fallings of the water levels inside of the infiltrometers measured directly in the paddy field presents Table 2.

Single ring infiltrometer of height 20 cm with inside diameter 8.5 cm was pressed vertically to the depth L(cm) = 7.0 under the soil surface of the experimental area of paddy field. The value of 2L (cm) = 14.0 characterizes the approximation of the supposed trajectory of the water particles in the terrain tested soil sample of paddy field.

The water table, which is identical with referential level, is approximately 4 cm above the surface of the experimental area of paddy field. A value of the level H0 (M), which represents the water table level in infiltrometer at the beginning of measurement at time t = 0 was H0 (mm) = 90.

A record of the vector of fallings Y(y1,y2…..yi……yn) is shown in the fourth column in Table 2 and represents Y-vector as dependent variable (known values). A vector of time X(t1, t2…..ti….tn) is presented in the third column in Table 2 and represents X-vector as independent variable (also known values).

With use of the nonlinear regression actually with help of the Marquardt search algorithm was determined the value of the parameter P1 (/min) from the equation (8). The results of the nonlinear regression model fitting show, that P1 (/min) = 0.000868 and determination coefficient R-squared = 0.987.

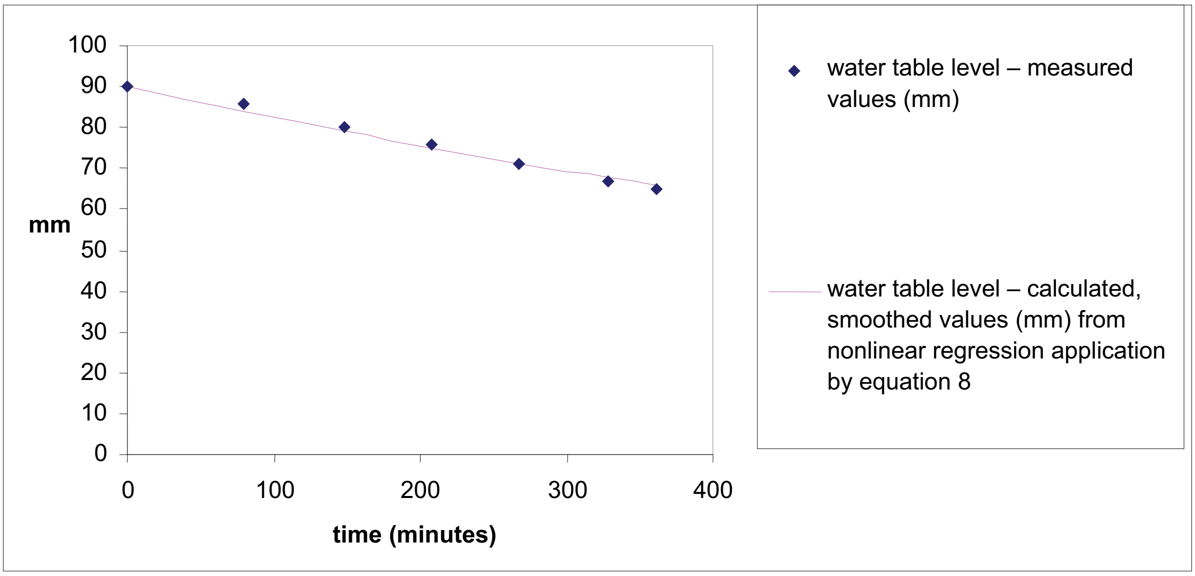
Tab. 2: Time series of measured and calculated values from the experimental area of paddy field in Taoyuan (Taipei, Taiwan)

20.03. 2001 Number of observation	Hours	Time (minutes)	Water table level – measured values (mm)	Water table level – calculated values (mm)
1	7.02	0	90. 0	90. 0
2	8.22	80	86. 0	84. 0
3	9.30	148	80. 0	79. 0
4	10.30	208	76. 0	75. 0
5	11.30	268	71. 0	71. 3
6	12.30	328	67. 0	67. 7
7	13.04	362	65. 0	65. 7

Tab. 3: Results of nonlinear regression analysis from an experimental area of paddy field in Taoyuan (Taipei, Taiwan)

Model Fitting Results				
parameter	estimation	standard error	ratio	
P1	0.000868	0.00002467	35.1996	
Total iterations = 3		Total function evaluations = 7		
Analysis of Variance for the Full Regression				
source	sum of squares	degrees of freedom	mean square	ratio
Model	41420.245	1	41420.245	36789.271
Error	6.7552703	6	1.1258784	
Total	41427.000	7		
Total (corr.)	537.71429	6		
R-squared = 0.987437		R-correlation = 0.993698		

Figure 3: Measured values and calculated, smoothed values from nonlinear regression application by equation (8), from the experimental area of paddy field in Taoyuan (Taipei, Taiwan).



Relation between vectors Y and X explains equation (8), where only unknown is parameter P1 (/T).
It is accepted, that P1 = K/2L, this means, that according to nonlinear regression analysis will be saturated hydraulic conductivity K (mm/min) = parameter P1×2L = 0.000868 × 140 = 0.1215 (m/min) = 2×10^{-6} (m/s).
(The results of model fitting and the analysis of variance for the full regression are presented in Table 3). With help of the known value of P1 (/min) = 0.000868 and by X-vector (t [min] = t1, t2…..ti….tn), according equation (8), respectively equation (9), the new values of the falling water heads in time t, inside of infiltrometers, from the level H0 = 90 mm, were recalculated and placed in the last column in Table 2. Measured data and their smoothing by nonlinear regression (equation /8/) are presented in Figure 3. High value of the determination coefficient R-squared = 0.987 reflects particularly good predicating ability of tested model, represented by equations (8).
The terrain measurements on the experimental paddy field proceeded from March 15 to March 25, 2001, when were realised, all in all, the tens of experimental measuring. During the measurements of the saturated hydraulic conductivities, was not recorded any sudden recharge (e.g. typhoons, rain storms or massive floods) to the water table level on the experimental paddy field.
The values of saturated hydraulic conductivities K (m/s), which were approximated by the direct experimental measurement on the paddy field, varied from 5×10^{-6} to 10^{-7} (m/s) and were successfully verified by the laboratory measurements on the "undisturbed" core samples in the non steady-state conditions by the falling head permeameters.
All data from the direct experimental measurement on Taoyuan's (Taiwan) paddy fields and all data from the laboratory verifications attend for other use at the Department of Land Use and Improvement, Faculty of Environmental Sciences, Czech University of Life Sciences Prague.

CONCLUSIONS

It is possible to suppose that the values of saturated hydraulic conductivity are true enough, because they were approximated from the data obtained by the direct experimental measurements on paddy fields.
The data obtained to determine the hydraulic saturated conductivities by direct field measurements during the cycle of the flooded period on paddy fields, that is after agricultural activities such as rice planting and paddy field maintenance were carried out, already reflect the impact of some surface layers compacting, which significantly influences the values of hydraulic saturated conductivities.
Therefore the results of saturated hydraulic conductivities obtained by the way described above are very valuable and objective, and are useful for the control of water management of paddy fields. The values of saturated hydraulic conductivities obtained from the laboratory by the verification of the experimental terrain measurements on paddy fields were fairly similar with the values of saturated hydraulic conductivities obtained by the direct paddy field measurements.
All processes of non-linear regression that were applied to determine the saturated hydraulic conductivities of surface layers of paddy fields yielded extremely high values of the determination coefficients R-squared, which fluctuated about 0.98, some even converged to 1. It not only shows the suitability of the method applied

for the solution of the problem, but also a particular forecasting ability of the tested model, in this case represented by equation (8). It ensues from the above that this method is relevant to the given problem, and that the K value is the best and the most plausible basis upon which to design and control the rice fields water management. This is a very significant finding in respect to the rice growing and water saving.

The values of saturated hydraulic conductivities of surface layers of paddy fields determined in this way are credible enough. Such data are necessary for the design of basic parameters of paddy fields irrigation and drainage systems, while they can also be used for the verification of the correctness and hydraulic efficiency of the designed systems.

Last but not least, the data of saturated hydraulic conductivities represent a suitable and simple tool for operative hydraulic control and optimization of paddy field water management, which will in result be friendly to water resources and will mitigate their vulnerability.

In addition, Kulhavy et al. (2008) in the research project with name “Hydrologic Regimes and Landscape Structures Optimization”, no. 2B06022, by which means was elaborated this article, and which is solved by Research Institute for Soil and Water Conservation (RISWC) Prague-Zbraslav, in co-operation with Department of Land Use and Improvement, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, for Ministry of Education Czech Republic, try, besides others, to optimize the water regime of river landscape.

And just a method of determination of saturated hydraulic conductivities of the surface layers in river landscape, situated under the water table (wetlands, peat swamps), described in this article, can serve as a good tool to control and to manage the water regime in some parts of river landscape, as are e.g. wetlands or peat swamps, in the hydrological conditions of the Czech Republic.

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