Estimation of precise irrigation rates taking into account the hysteresis of soil water-retention capacity

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Abstract: A method is proposed to calculate water irrigation rates for crops that considers hysteresis in the volumetric water content ($\theta$)-water pressure head ($\psi$) relations, including scanning paths, by the method of point approximation. Three $\theta(\psi)$ models are described and computational experiments were carried out using data from literary sources on the hydrophysical properties of soils with different textures. The error analysis of the point approximation of the main branches and the predictive calculation of the scanning branches of the hysteresis loop were carried out. The practical significance of the research lies in the possibility to calculate the precise irrigation rates for crops. The use of such standards minimizes unproductive spending of irrigation water, fertilizers, ameliorants and plant protection products, as well as prevents the pollution of natural waters with agrochemicals and reduces the risk of eutrophication of water sources.

1. Introduction

In connection with the observed climate change, the problem of accurately assessing the irrigation rates for crops becomes very relevant, especially in arid zones of farming. The solution of this problem is of great importance both economically and ecologically. Preventing excess water runoff from the root zone limits means: economically - reducing the costs of crop production in irrigated farming by minimizing unproductive spending of irrigation water, fertilizers, ameliorants and plant protection products; ecologically - a decrease in the level of pollution of natural waters with agrochemicals leached from the soil by excess moisture, and also - a reduction in the risk of eutrophication of water sources.

After watering, the change of soil moisture conditions during evapotranspiration is determined by the soil water-retention capacity (SWRC), which is described as a dependence of the volumetric water content $\theta$ [cm³·cm⁻³] on the pressure head of soil moisture $\psi$ [cm H₂O]. As is well known, the nature of this hydrophysical property of the soil is hysteresis, which infers different $\psi$ values will be measured depending on whether $\theta$ is increasing or decreasing. The $\theta(\psi)$ curves constructed from the measured points obtained under drying conditions describes drying branches of SWRC hysteresis. The $\theta(\psi)$
curves constructed from the measured points obtained under wetting conditions describes wetting branches of SWRC hysteresis.

There is a singular point on this curve that marks the boundary of the transition of water from the category of gravitational to the category of capillary-suspended moisture. Value $\theta$, which corresponds to this point, is called the field capacity (FC) of the soil. The difference between FC and the value of the pre-irrigated soil moisture (PSM) is usually used in the calculating irrigation rates; the minimum of the subtracted value of this difference is the moisture of capillary break (CB) \[1\]. In order to optimize the conditions for the moisture supply of agricultural plants, irrigation in practice begins at a slightly higher value of CB in the root zone of the soil. A question is: Is the soil able to retain all moisture at the rate calculated by the formula FC minus PSM? If there was no hysteresis $\theta(\psi)$, then the answer would be yes.

In the presence of hysteresis, the wetting branches, but not the drying branches $\theta(\psi)$ describe the sequence of soil water states in a moistened soil. In this case, the main (boundary) wetting branch and all scanning (internal) branches of the hysteresis loop are below the main (boundary) drying branch. This means that at the normal conditions, calculated by the formula FC minus PSM, the $\theta$ value reaches FC, and the negative pressure head of moisture for some time is greater than $\psi$ under FC, which corresponds to the main drying branch $\theta(\psi)$. In this case, an excess of gravitational moisture is formed, which flows outside the root zone of the soil. Therefore, when calculating the irrigation rates, it is necessary to use not FC, but the $\theta$ value on a given wetting branch, which corresponds to the $\psi$ under FC. However, it is not known in advance in the conditions of the agricultural field which scanning wetting branches $\theta(\psi)$ will be needed to calculate the irrigation rates. Measurements of scanning branches are very laborious, and it is almost impossible to measure all scanning branches.

If irrigated farming is carried out in conditions protected from atmospheric precipitation, then this problem can be solved by using in calculations of irrigation rates a predetermined and measured wetting branch of SWRC. However, this technique has disadvantages because with the oscillation of capillary pressure in a fixed interval, some drift of $\theta$ value may occur in the range bounded by the main branches of the hysteresis loop of SWRC. In such a case, a series of measurements of scanning branches corresponding to each new oscillation will be required.

If crops are cultivated in natural (rainfed) conditions, then at the beginning of precipitation, soil moisture transfers from the conditions described by the main drying branch to the conditions described by scanning primary wetting branches, which start from the corresponding turning points. The positions of the turning points are not known in advance because of the probabilistic nature of meteorological forecasts. The end of precipitation leads to the transition to the scanning secondary drying branches from turning points, whose positions are also not known in advance. From this, it becomes clear that to take into account possible scenarios of atmospheric soil moisturizing, an unlimited number of measurements of the scanning branches of the hysteresis loop will be required, which is practically impracticable. Thus, the only possible method of obtaining data on the scanning branches of the hysteresis loop is mathematical modeling.

The main objective of this study is to simulate the hysteresis of SWRC: to identify the parameters of the presented model using a point approximation of data on the main branches with subsequent prediction of the hysteresis loop scanning branches and the calculation of precise irrigation rates.

2. Materials and methods

In many papers, two well-known models of hysteresis [1-3] are utilized. The first is the model of Scott et al. [4] and the second is the model of Kool and Parker [5]. The first model is based on the function $\theta(\psi)$ proposed by Haverkamp et al. [6]; the second model is based on the function $\theta(\psi)$ proposed by Van Genuchten [7]. In this research, it is proposed to use improved functions of Kosugi [8] and Haverkamp et al. [6] in the Scott et al. model. Improvement is achieved by using an additional additive parameter $\psi_e$. Table 1 shows three models of hysteresis.
Table 1 Functions $\theta(\psi)$ used in hysteresis models

| Hysteresis model | Model designation | Function # | Functional description |
|------------------|-------------------|------------|------------------------|
| Kool and Parker  | Hys-KPVG          | 1          | $S_e = \begin{cases} \frac{1}{m} [1 + (-\alpha \psi)^n]^{-m} \psi \leq 0; \\ 1, \, \psi \geq 0. \end{cases}$ |
| Scott et al. with enhanced $\theta(\psi)$ of Kosugi | Hys-SKT         | 2          | $S_e = \begin{cases} \frac{1}{2} \text{erfc} \left( \frac{n\sqrt{n}}{4} \ln(-\alpha(\psi - \psi_e)) \right), \psi < \psi_e; \\ 1, \, \psi \geq \psi_e. \end{cases}$ |
| Scott et al. with enhanced $\theta(\psi)$ of Haverkamp et al. | Hys-SHT         | 3          | $S_e = \begin{cases} \left(1 + (-\alpha(\psi - \psi_e))^n\right)^{-1}, \psi < \psi_e; \\ 1, \, \psi \geq \psi_e. \end{cases}$ |

Table 1 uses the following notations: $\text{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt$ – complementary error function; $S_e = (\theta_0 - \theta_s)/(\theta_d - \theta_f)$ – effective moisture saturation of the soil; $\theta_0$ [cm$^{-3}$ cm$^{-3}$] – volumetric water content at full water saturation of the soil; $\theta_d$ [cm$^{-3}$ cm$^{-3}$] – volumetric water content corresponding to the minimum specific volume of moisture as a fluid in the soil; in function #1 $\alpha$ [cm H$_2$O$^{-1}$], $n$ and $m$ – empirical parameters ($m = 1 - 1/n, \, n > 1$); in functions #2 and #3 $n > 0, \, \alpha = -1/(\psi_0 - \psi_e)$ [cm H$_2$O$^{-1}$], $\psi_e$ [cm H$_2$O], $\psi_0$ [cm H$_2$O$^{-1}$]$< \psi_e$ – interpreted parameters (for drying branches $\psi_e = \psi_{e,d} \leq 0$, for wetting branches $\psi_e = \psi_{e,w} \geq 0$); under $\psi_e=0$ functions #2 and #3 accordingly reduced to the models of SWRC by Kosugi, as well as by Haverkamp et al. In hysteresis models, turning points are calculated using the algorithm by Scott et al. [4], which is presented in table 2.

Table 2 Scanning drying and wetting branches of $\theta(\psi)$ by Scott et al. [4]

| Scanning drying branches, starting from the $i$-th point on the wetting branch | Scanning wetting branches, starting from the $j$-th point on the drying branch |
|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| $\theta = \theta_r + (\theta_s^* - \theta_r)S_{e,d};$ | $\theta = \theta_r^* + (\theta_s - \theta_r^*)S_{e,w};$ |
| $\theta_r^* = \theta_r, \psi_{e,w} \leq \psi_i, \psi < \psi_{e,d};$ | $\theta_r^* = \theta_r, \psi_j \ll \psi_{e,d}, \psi_j \leq \psi < \psi_{e,w};$ |
| $\theta_s^* = \theta_s, \psi_{e,w} \leq \psi_i, \psi < \psi_{e,d};$ | $\theta_s^* = \theta_s, \psi_{e,d} \leq \psi_j, \psi < \psi_{e,w};$ |
| $\theta_i^* = \theta_i - \theta_r \left(1 - S_{e,d}(\psi_i)\right),$ | $\theta_j = \theta_s, \psi_{e,d} \leq \psi_j, \psi_{e,d} \leq \psi \leq \psi_i,$ |
| $\psi_{e,d} < \psi_i, \psi_i \leq \psi_i,$ | $\psi < \psi_{e,d}, \psi_j \leq \psi < \psi_{e,w};$ |
| $\theta = \theta_r, \psi_{e,w} \leq \psi_i, \psi_{e,d} \leq \psi \leq \psi_i,$ | $\theta = \theta_s, \psi_{e,d} \leq \psi_j, \psi_j \leq \psi_j,$ |
| $\theta = \theta_s,$ $\psi_{e,d} \leq \psi_i, \psi_{e,d} \leq \psi \leq \psi_i.$ | $\theta = \theta_s, \psi_{e,d} \leq \psi_j, \psi_j \leq \psi_j.$ |

The literature data on the water-retention capacity of soils with different textures from the Mualem catalog were used to solve the problems posed in the research: *Molonglo river sand, Carieol silt loam, Rubicon sandy loam, Ida silt loam* (0-15 cm) [9].

At the Water Management and Hydraulic Engineering Department of Peter the Great St.Petersburg Polytechnic University, a computer program «Soil-Hysteresis» has been developed to implement computational experiments with the three models of SWRC hysteresis presented in the research.
3. Results and discussions

Using the computer program «Soil-Hysteresis», the following computational experiments were carried out: 1) identification of the model parameters using the point approximation method of measured data on the main (boundary) drying and wetting branches of SWRC; 2) prediction of the scanning branches of the hysteresis loop. The resulting parameter values are given in Table 3. In this research, equal values of the parameters \( n_d = n_w \) were used, this eliminates the manifestation of an artificial «pump effect», i.e. when capillary moisture pressure oscillates in a fixed range of values, the scanning branches do not go beyond the boundaries of the physically permissible region.

### Table 3 Parameters of the soil hydrophysical functions

| Soil                     | Model | \( \theta_r \) | \( \theta_s \) | \( \psi_{e,d} \) | \( \psi_{0,d} \) | \( \alpha_d \) | \( \psi_{e,w} \) | \( \psi_{0,w} \) | \( \alpha_w \) | \( n_d = n_w \) |
|--------------------------|-------|----------------|----------------|-----------------|----------------|---------------|----------------|----------------|---------------|----------------|
| Mo- longlo river sand    | Hys-KPVG | 0.0536        | 0.277          | -9.90           | 0.101          | -6.75         | 0.148          | 2.16           |               |                |
|                          | Hys-SKT | 0.0808        | 0.277          | 0               | -14.4          | 0.0695        | 5.00           | -9.21          | 0.0704        | 2.57           |
|                          | Hys-SHT | 0.0774        | 0.277          | 0               | -14.7          | 0.0683        | 4.79           | -9.47          | 0.0701        | 2.59           |
| Ca- rieol silt loam      | Hys-KPVG | 0.316         | 0.442          | -97.8           | 0.0102         | -34.3         | 0.0291         | 2.78           |               |                |
|                          | Hys-SKT | 0.318         | 0.442          | 0               | -128           | 0.0078        | 35.9           | -45.1          | 0.0123        | 2.79           |
|                          | Hys-SHT | 0.317         | 0.442          | 0               | -129           | 0.0078        | 36.3           | -45.7          | 0.0122        | 2.89           |
| Rubi- con sandy loam     | Hys-KPVG | 0.170         | 0.381          | -76.9           | 0.0136         | -27.0         | 0.0378         | 3.30           |               |                |
|                          | Hys-SKT | 0.173         | 0.381          | -29.2           | -93.0          | 0.0157        | 30.0           | -35.6          | 0.0153        | 3.42           |
|                          | Hys-SHT | 0.175         | 0.381          | -18.1           | -89.5          | 0.0140        | 27.0           | -32.4          | 0.0168        | 3.68           |
| Ida silt loam            | Hys-KPVG | 0.00          | 0.554          | -59.3           | 0.0169         | -21.8         | 0.0460         | 1.23           |               |                |
|                          | Hys-SKT | 0.166         | 0.554          | 0               | -348           | 0.0029        | 36.1           | -174           | 0.0048        | 1.01           |
|                          | Hys-SHT | 0.173         | 0.554          | 0               | -338           | 0.0030        | 36.0           | -162           | 0.0050        | 1.07           |

Table 4 shows the correlation coefficients between measured and calculated data on the hysteresis branches of SWRC. The highest value of the correlation coefficient for each branch is shown in bold.

### Table 4 Correlation coefficients between the calculation results and measured data on the branches of SWRC hysteresis
Correlation coefficient Models

| Soil                      | Hysteresis branches | Hys-KPVG | Hys-SKT | Hys-SHT |
|---------------------------|---------------------|----------|---------|---------|
| **Molonglo river sand**   | Main (boundary): identification by 21 points | 0.9911 | 0.9980 | 0.9980 |
|                           | Primary wetting: estimation for 25 points | 0.9835 | 0.9921 | 0.9904 |
|                           | Primary drainage: estimation for 32 points | 0.9884 | 0.9895 | 0.9902 |
|                           | Secondary drying branch: estimation for 6 points | 0.9976 | 0.9979 | 0.9979 |
| **Carieol silt loam**     | Main (boundary): identification by 72 points | 0.9886 | 0.9967 | 0.9967 |
|                           | Scanning wetting: estimation for 56 points | 0.9793 | 0.9934 | 0.9925 |
|                           | Scanning drainage: estimation for 85 points | 0.9925 | 0.9938 | 0.9936 |
| **Rubicon sandy loam**    | Main (boundary): identification by 74 points | 0.9711 | 0.9941 | 0.9920 |
|                           | Scanning wetting: estimation for 33 points | 0.9495 | 0.9941 | 0.9941 |
|                           | Scanning drainage: estimation for 26 points | 0.9702 | 0.9828 | 0.9858 |
| **Ida silt loam**         | Main (boundary): identification by 58 points | 0.9830 | 0.9970 | 0.9968 |

Table 5 shows the errors of identification of model parameters by the point approximation of data on the main (boundary) branches and the estimation errors of the scanning hysteresis branches (RMSE - the square root of the arithmetic mean of the squares of the deviations of the calculation results from the measured data). The minimum error values are in bold.

**Table 5** Comparison of the errors of the point approximation of data on the main (boundary) branches and the errors in estimating the scanning branches of SWRC hysteresis.
Rubicon sandy loam

| Parameter                               | Scanning wetting: estimation for 56 points | 0.0080 | 0.0058 | 0.0062 |
|-----------------------------------------|-------------------------------------------|--------|--------|--------|
| Scanning drainage: estimation for 85 points |                                           | 0.0054 | 0.0048 | 0.0050 |
| Main (boundary): identification by 74 points |                                           | 0.0150 | 0.0069 | 0.0084 |
| Scanning wetting: estimation for 33 points |                                           | 0.0349 | 0.0057 | 0.0100 |
| Scanning drainage: estimation for 26 points |                                           | 0.0177 | 0.0181 | 0.0135 |
| Ida silt loam                            | Main (boundary): identification by 58 points | 0.0214 | 0.0089 | 0.0089 |

In figures 1-3 points indicate the measured data, and solid curves show the results of the point approximation of the main (boundary) branches, as well as the prediction results of the scanning hysteresis branches.

**Figure 1a** Point approximation of data on the main (boundary) branches; evaluation of three scanning soil wetting branches of the soil «Molonglo river sand» using the model Hys-KPVG ($n_d=n_w$)

**Figure 1b** Point approximation of data on the main (boundary) branches; evaluation of four scanning drying branches of soil «Molonglo river sand» using the model Hys-KPVG ($n_d=n_w$)
Figure 2a Point approximation of data on the main (boundary) branches; evaluation of three scanning soil wetting branches of the soil «Carieol silt loam» using the model Hys-SKT ($n_d=n_w$)

Figure 2b Point approximation of data on the main (boundary) branches; evaluation of four scanning wetting branches of soil «Carieol silt loam» using the model Hys-SKT ($n_d=n_w$)

Figure 3a Point approximation of data on the main (boundary) branches; evaluation of five scanning wetting branches of soil «Rubicon sandy loam» using the model Hys-SHT ($n_d=n_w$)

Figure 3b Point approximation of data on the main (boundary) branches; evaluation of four scanning drying branches of soil «Rubicon sandy loam» using the model Hys-SHT ($n_d=n_w$)

According to all estimates presented in the research, the errors of approximation of data on the main branches and the prediction errors of the scanning branches of SWRC hysteresis, the Hys-KPVG model is significantly inferior to the Hys-SKT and Hys-SHT models. The closest correlation is observed in the
point approximation of measured data on the main branches: the correlation coefficients for all three models differ slightly, however, the error of the Hys-KPVG model remains the greatest, and the Hys-SKT and Hys-SHT models have no significant differences. This trend continues in the prediction of scanning branches. Thus, we can conclude that in the soil hydrophysical calculations the use of the models Hys-SKT and Hys-SHT seems to be the most preferable. For calculating the precise irrigation rates, it is recommended to use the Hys-SHT model, since it uses in practical terms the preferred approximation of the function $\theta(\psi)$.

The following is the algorithm for calculating the precise irrigation rates for the soil *Ida silt loam*. The pressure head of soil moisture at FC is calculated using the formula [10, 11]:

$$\psi_{FC} = 10^{2.17+FC/\rho_b}$$

where $\rho_b$ - bulk density of the soil [g·cm$^{-3}$].

This formula describes the so-called Voronin’s «secant» that intersects the SWRC curve at the point corresponding to FC. For soil *Ida silt loam* ($\rho_b=1.24$ [g·cm$^{-3}$]) at the point where the SWRC curve created using the Hys-SHT model and the identified parameters (Table 3) intersects with the Voronin’s «secant», $\psi_{FC}$ and FC on the main drying branch: ($\psi_{FC} = -302.5$ [cm H$_2$O]; FC = 0.375 [cm$^3$·cm$^{-3}$]) (figure 4). As an example, the value of the pre-irrigated soil moisture (PSM), where the primary wetting branch begins, is assumed to be 0.282 [cm$^3$·cm$^{-3}$]. It corresponds to $\psi$, which is equal to -800 [cm H$_2$O].

In accordance with the currently used method of practice, amelioration agents apply such irrigation rate, which should have moistened the soil to FC value. However, at the rate calculated by the difference of FC minus PSM, there is an excess of gravitational moisture, due to which unproductive losses of irrigation water occur. This research proposes to calculate the irrigation rate at which the soil reaches some state characterized by the corresponding point on the Voronin’s «secant», and the volume moisture of the soil does not rise to the value of FC corresponding to the main drying branch. When creating the primary wetting branch to the point of intersection with the Voronin’s «secant», we obtain the value of the volumetric water content $\theta_1 = 0.346$ [cm$^3$·cm$^{-3}$]. In this case, an excess of gravitational moisture is not formed, and all the moisture is retained by the soil and is gradually consumed on the absorption by the roots of cultivated plants.

If the «traditional» method of irrigation is used, after $\theta$ reaching the value that is equal to 0.375 [cm$^3$·cm$^{-3}$], the excess moisture flows down by the secondary drying branch, while it reaches the value corresponding to the intersection point of the secondary drying branch with the Voronin’s «secant». This value is equal to $\theta_2 = 0.344$ [cm$^3$·cm$^{-3}$]. It follows that for the «traditional» method of irrigation, the unproductive loss of moisture (in units of $\theta$) flowing outside the root zone is equal to $\Delta = FC - \theta_2 = 0.375 - 0.344 = 0.031$ [cm$^3$·cm$^{-3}$]. Therefore, for an irrigated area of 1 hectare with a wetting of 30 cm soil layer, an unproductive loss of moisture will be: $0.031 \times 0.3 \times 10^4 = 93$ [m$^3$·ga$^{-1}$].

It should be noted that the land reclamation practitioners, of course, know about these water losses (and associated costs in the production of irrigated farming) [12-15]. However, it has not been possible to calculate the irrigation rates more accurately until the measurement of the scanning branches (especially the wetting branches) is very laborious, and it is impossible to predict in advance (in terms of the agricultural field) which particular hysteresis branches will be necessary. In this case, the application of the mathematical model of hysteresis $\theta(\psi)$ is essentially unopposed [16-19].
4. Conclusion
According to the results of the research, it can be concluded that the «Soil-Hysteresis» program can significantly simplify the assessment of soil hydrophysical indicators; and at the same time, a lower estimation error of the Hys-SHT model is achieved in comparison with the errors of analogical models. With usage of the results reported at this paper, a reduction in costs during the pre-project engineering surveys in hydraulic engineering construction, as well as lowering the cost of plant production in irrigated farming are expected. The use of precise irrigation rates calculated applying offered model will prevent the run-off of excess free (gravitational) moisture and, therefore, minimizes the loss of irrigation water, as well as unproductive spending of nutrients, ameliorants and plant protection products due to leaching of agrochemicals beyond the root layer of the soil. Thus, significant environmental and economic effectiveness will be achieved in the design and operation of hydraulic engineering facilities, such as irrigation and drainage systems.

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