Irrigation management model based on soil moisture distribution profile

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Abstract. The article is devoted to the actual problem solving of precision irrigation in terms of an irrigation management model creating based on the soil moisture spatial variation. The research key element is that the model being created takes into account the soil moisture content variability not according the area of the irrigated plot, but in the vertical profile of the agricultural crops active root water consumption zone. This approach avoids the necessity for the irrigation equipment design complication for irrigation moisture differentiated distribution and therefore the technology application allows us to avoid unnecessary costs. The irrigation requirement assessing block according to the moisture content differentiating in the active soil layer profile is new in the proposed model architecture. The block algorithm assumes the two-stage irrigation requirement assessment, first, based on the total level of soil moisture variation in the active layer profile and second, on the layers sum of the active soil horizon with a moisture content below the threshold level. Together, these estimates allow us to make a decision about the irrigation necessity if soil moisture excessive variation in the profile layers and the moisture distribution nature in the soil profile have a significant impact on the irrigated crop productivity.

1. Introduction
Irrigation reclamation today is the means for the agricultural plants environment multi-factor regulation [1-3]. One of the key tasks of the hydraulic reclamation development at the present stage is the dosed impacts accuracy increase on the entire field of involved regulators. Technologies should take into account the crop cultivation conditions spatial variability and therefore the spatial requirement for regulators dosed impact [4]. The research purpose is to create an irrigation management model based on the soil moisture spatial variation.

2. Materials and methods
The precise irrigation problem in the world science already has a certain history with not always positive results [5, 6]. It is primarily about the irrigation water dosed distribution over the irrigated area, taking into account the soil moisture actual variability. Indeed, such technologies require significant complexity in the irrigation equipment design and there is a need to compile the digital maps of the soil moisture content. The latter is a knowledge-intensive and expensive technology that has not yet been objectively successfully implemented in the irrigated agriculture practice. The effect of precision irrigation technologies use did not always exceed the additional costs [7].
It should be pointed out that these researches and inventions were primarily focused on soil moisture variations compensating over the irrigated plot area. However, the problem should be considered in volume, not in area. This means that it is necessary to take into account the soil moisture vertical variability, at least, within the active root water consumption zone. This task does not require irrigation water differentiated distribution over the irrigated plot area and therefore, conventional irrigation equipment can be used.

The technology assumes only an irrigation date shift, if the excessive soil moisture variability in the profile has an objective effect on crop yield. The approach effectiveness was confirmed by the results of the authors' own researches implemented in irrigated soybean crops [8]. However, an irrigation management model based on the soil moisture distribution profile, which illustrates how this could be implemented within modern irrigation technologies, has not been proposed yet.

3. Results and discussion

Figure 1 presents a generalized view of the hydro-reclamation technologies management in the irrigation field in the integrated executive blocks format. The combination of such executive blocks makes up an integrated irrigation management model; most of the model components are generalizations of already known and used information technologies in the industry [9, 10]. These components are highlighted in blue in the figure.

Like any management information system, irrigation management is based on the input data set analysis. Therefore, the input executive block of the integrated irrigation management model is the input data aggregation. The model traditionally includes two large executive blocks that differentiate the irrigation planning problems and the operational irrigation management problems solving.

Irrigation planning allows us to solve at least two important tasks. This is the task of the technical system optimizing used for hydraulic reclamation and the task of resources consumption mode optimizing. Regarding the technical system design solutions and design parameters, the optimization problem has the following form:

\[
\sum CD_{opt} = f(\sum CD; \sum DP),
\]

where \( F(mt) \) is the main technological function of the technical system; \( F(mt)_{Thr} \) is the threshold (lower) level of the basic technological functions implementation; \( \sum CD \) is the set of the technical system constructive solutions; \( \sum DP \) is the set of technical system technical parameters; \( Pr \) is the constructive decision price of a parameter relative to the base design. The second one involves the problem solving of water resources optimal distribution based on the already known technical system capabilities. The problem statement is as follows:

\[
F(R \cdot CR \cdot D) = \max_{D_{st} < D < D_f} \sum_{CR_1 < CR < CR_j} (Y_{CR, D} \cdot Pr_{CR} - R_{CR, D} \cdot Pr_R)
\]

where \( Y_{CR, D} \) is the crop seeding productivity (CR), t/ha; \( R_{CR, D} \) is resource costs for agricultural crops irrigation (CR) at the irrigation date (D); \( F(R \cdot CR \cdot D) \) is the target function of combined resource use (R) in agricultural crops seeding (CR) on the date (D); \( Pr_{CR} \) is the price of irrigated agricultural crops products; \( Pr_R \) is the resource price consumed for agricultural crops irrigation; \( [D_{st}; D_f] \) is the valid dates of crops irrigation for compromise solutions adoption in conditions of resource supply shortage \([CR_1; CR_j] \) is the agricultural crops integration, the decision about the priority irrigation dates, which is the result of optimization calculations.
The irrigation requirement problem on the operational level is solved on the basis of information about current soil moisture reserves by comparing them with a species-specific threshold level. In this case, in the classic version, the irrigation requirement assessment is carried out based on the moisture reserves average value in the active (calculated) soil horizon:

$$W_{\text{Mid}} = f(W_{i-1\text{Mid}} \sum a_i), \quad W_{\text{Mid}} = W_{\text{Mid}} - K_{W_{\text{Mid}}} W_{\text{Thr}}$$  \hspace{1cm} (3)

where $W_{\text{Mid}}$, $W_{\text{Mid}}$ is the average actual moisture reserves in the active (current) soil layer, mm; $W_{i-1\text{Mid}}$ is the average moisture reserves in the active soil layer prior to the estimated date, mm; $\sum a_i$ is the factors sum that determine the final vector of soil moisture balance during the base period; $K_{W_{\text{Mid}}}$ is the irrigation requirement criterion; $W_{\text{Thr}}$ is the soil moisture threshold level, mm.

If the dimensionless criterion is less than or equal to one, the irrigation requirement is confirmed. According to the proposed model, in this case, a check of the irrigation technological feasibility within the specified time frame is started and, if a positive decision is made, the technological parameters of irrigation are calculated. If irrigation cannot be carried out within the time set by the calculation, the irrigation date technological shift parameters are calculated, as well as the possible consequences of the optimal irrigation regime delay are estimated.

If the dimensionless criterion is greater than one, the irrigation requirement is rejected. In the classic version, this solution was sufficient, in the future, it was assumed to evaluate the likely date of
Irrigation (forecast), select the step of calculations iteration and timer programming to initiate a new calculation cycle. An important distinctive block of the proposed irrigation management model is an additional calculations cycle to assess the irrigation requirement based on the differentiation of moisture reserves to the soil profile. In figure 1 this model component is highlighted in red.

The algorithm for irrigation requirement determining based on the moisture reserves differentiation to the soil profile is shown in figure 2. The algorithm assumes two scenarios implementing possibilities for evaluating the differentiation of moisture content by the soil profile, the first of which involves the soil moisture movement modeling at known values of the factors combinations $\sum b_i$:

$$\beta_i = f(\sum b_i)$$

where $b_i$ is the coefficient of soil moisture variation in the profile of the calculated layer, %.

![Figure 2. Algorithm for determining the irrigation requirement based on soil moisture distribution profile.](image)

The total vector $\sum b_i$ is a generalization of current data on the soil water-physical properties, atmospheric precipitations, the plot hydrological features, moisture reserves distribution data along the soil horizons at the beginning of the calculation period, etc. The full factors composition that determine the vector $\sum b_i$ is characterized by the model of vertical moisture exchange used in calculations. Another method of estimating soil moisture content differentiated by profile is the use of physically measured (sensory) data $W_{sh}$, which characterize the layer-by-layer moisture distribution. The method involves the use of multi-point sensors that are vertically oriented within the lines of at least the active (calculated) soil layer. The function $\beta_i = f(W_{sh})$ has the following solution:

$$\beta_i = \sqrt{\frac{\sum_{i=1}^{n} (W_{sh_i} - W_{shMid})^2}{n-1}}$$

where $W_{shMid}$ is the moisture content in the mid-layer of the soil profile.
where $n$ is the total number of selected soil horizons within the active layer; $W_{s\varepsilon_h}$ is the soil moisture content in the selected soil horizon $\varepsilon$ within the active layer $h$, mm; $W_s$ is the measured average moisture content of the active soil layer, mm.

Hence, the criterion for irrigation requirement due to moisture content variability excess in the profile of the active soil layer is determined from the formula:

$$K_\beta = \frac{\beta_i}{\beta_{Thr}},$$

$$K_\beta < 1: \text{no irrigation required}, K_\beta \geq 1: \text{include irrigation}$$

where $K_\beta$ is the irrigation requirement criterion due to the moisture content variability excessive in the profile of the active soil layer; $\beta_{Thr}$ is threshold value of the soil moisture variation coefficient in the profile, above which it is impossible to exclude the irrigation requirement with the purpose of water supply conditions alignment in the soil profile, %.

The threshold level of the soil moisture variation coefficient in the profile is based on the results of solving the optimization problem:

$$\Delta Y_\beta \cdot Pr > C_W,$$

$$\beta_{Thr} = \min_{\Delta Y_\beta \cdot Pr > C_W} \beta$$

where $\Delta Y_\beta$ is the change (decrease) in the irrigated crop yield when the soil moisture reserves vary according to the profile $\beta$, t / ha; $Pr$ is the yield price, c.u.; $C_W$ is the prime cost of additional irrigation to equalize the soil moisture content in the profile, c.u.

If the $K_\beta$ criterion values range from zero to one, irrigation is not required. If the value of this criterion becomes equal to or greater than one, another check is performed on the value of the $h$ profile with the moisture content less than the $W_{Thr}$ threshold:

$$K_h = \frac{h_{W \leq W_{Thr}}}{h_{W \leq W_{Thr}}},$$

$$K_\beta < 1: \text{no irrigation required}, K_\beta \geq 1: \text{include irrigation}$$

where $K_h$ is irrigation requirement criterion due to excessive differentiation of the soil profile by the moisture degree; $h_{W \leq W_{Thr}}$ is the proportion of the calculated soil moisture below pre-irrigation moisture level, %; $h_{W \leq W_{Thr}}$ is the threshold shares value of the estimated soil layer with the moisture content below the pre-irrigation moisture level, %.

If the $K_h$ criterion values do not exceed one, it is assumed to conclude that there is no need for another vegetation irrigation. When the $K_h$ criterion values are equal or greater than one, we make a conclusion about the need for irrigation to equalize excessive (agro-biologically and economically significant) uneven moisture distribution along the soil profile.

4. Conclusion

The irrigation management model based on the early irrigation requirements in order to decay excessive moisture distribution unevenness along the active soil layer profile was proposed. The irrigation requirement assessing block according to the moisture content differentiating in the active soil layer profile is new in the proposed model architecture.

The block algorithm assumes the two-stage irrigation requirement assessment, first, by the total level of soil moisture variation in the active layer profile, and then by the layers sum of the active soil layers with a moisture content below the threshold level. Together, these estimates allow us to make a decision about the irrigation necessity if soil moisture excessive variation in the profile layers and the moisture distribution nature in the soil profile have a significant impact on the irrigated crop.
productivity. In this case, the irrigation is justified if its prime cost is obviously lower than the cost of additional products obtained as the result.

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