Justification of methodological approaches to standardisation of irrigation as an element of resource saving and minimization of the anthropogenic load on agrobiocenosis

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Abstract. The analysis shows that the value of agricultural crops' evapotranspiration is influenced by many non-linearly changing factors in the closed system “soil - plant - atmosphere”. Therefore, the method of determining evapotranspiration is complemented by computational models, with the help of which evapotranspiration is determined with a sufficient degree of accuracy from the results of actual observations, including the hydrometeorological parameters of the corresponding irrigated areas, followed by comparison of these values with data obtained when determining potential evapotranspiration on the existing networks of hydrometeorological and water balance stations. As a result of research, empirical dependencies of multivariate determination of evapotranspiration, as well as on moisture reserves in the calculated soil layer and potential evapotranspiration, were established, taking into account the growth and development phases and the microclimatic coefficient of the summer planting period. The above methodological approach substantiates the new water and energy saving methods of forecasting, planning of irrigation processes of agricultural crops and operation-al management based on the spatial and temporal variability of hydrometeo parameters and actual moisture reserves in the calculated soil layer for the conditions of use of livestock waste.

1. Introduction
Evapotranspiration of agricultural crops has significant spatiotemporal variability, therefore the establishment of its optimal norm should be considered as a methodology for determining forecast indicators [1, 2]. They are established by retrospective calculation of evapotranspiration on the basis of observations of meteorological parameters during the required time period and an appropriate statistical analysis. In this way, the most probable values are obtained both for the near and long term [3-5]. The methodology for predicting evapotranspiration is based on the improvement of the bioclimatic method. It is necessary to know its actual value, which provides [6, 7]:

- calculation of evapotranspiration taking into account the dynamics of soil moisture in the calculated layer, as well as the variability of hydrometeorological parameters of a particular year;
• taking into account the effect of groundwater recharge on the indicators of evapotranspiration;
• determination of the amount of irrigation water infiltration beyond the limits of the design layer;
• establishment of the dynamics of evapotranspiration deficit and irrigation regimes for years of different water availability, taking into account the spatial and temporal variability of hydrometeorological parameters and actual moisture reserves in the calculated soil layer.

2. Materials and methods

The data obtained during water balance and agrometeorological studies by scientists of the Federal state budget scientific establishment «The Russian scientific research institute of land improvement problems» and Don state agrarian university for the period from 1990 to 2016, as well as materials of the Federal state budget scientific establishment «The Russian scientific research institute of land improvement problems» researches were used for 1960–1980 [8-11] to assess the influence of hydrometeorological factors and soil moisture variability on the evapotranspiration of various crops.

The studies, which were based on the dependences of the bioclimatic coefficients were carried out over a five-year period in Agroenterprise Bessergenevskoye LLC, the village of Bessergenevskaya of the Oktyabrsky district of the Rostov region [12, 13].

The ameliorative system is also filled with treated animal waste, therefore, constant monitoring of changes in the salt composition of the water used for irrigation is carried out (Table 1).

| Salt composition | Cl\(^-\) | SO\(_4^{2-}\) | HCO\(_3^-\) | Ca\(^{2+}\) | Mg\(^{2+}\) | Na\(^+\) | K\(^+\) | Ion sum | Dry residue | pH |
|------------------|------|------|------|------|------|------|------|-------|-------------|-----|
| gr               | 0,16 | 0,22 | 0,265 | 0,087 | 0,048 | 0,131 | 0,93  | 0,94   | 7,9         |
| mmol             | 4,9  | 4,77 | 4,33  | 4,5   | 3,86  | 5,66  |       |       |

3. Results and discussion

The authors established paired coefficients of their correlation with evaporation \( (E_\omega) \), air temperature \( (t) \), lack of air humidity \( (d_\phi) \), precipitation \( (P) \), lack of natural humidification \( (E_\omega - P) \), evapotranspiration \( (ET) \) and irrigation th rule \( (M) \), which is based on many years of research by scientists of the Federal state budget scientific establishment «The Russian scientific research institute of land improvement problems» and Don state agrarian university to study the dynamics of evapotranspiration of various crops depending on changes in actual meteorological parameters measured at the corresponding meteorological stations for the conditions of specific irrigated arrays. (table 2) [14, 15].

| Indicator         | \( E_\omega \) | \( t \) | \( d_\phi \) | \( P \) | \( E_\omega - P \) | \( ET \) | \( M \) |
|-------------------|---------------|-------|-------------|-------|-----------------|-------|------|
| \( E_\omega \)    | 1,00          | 0,90  | 0,94        | 0,81  | 0,83            | 0,96  | 0,74 |
| \( t \)           | 0,34          | 1,00  | 0,80        | 0,82  | 0,90            | 0,73  | 0,58 |
| \( d_\phi \)      | 0,94          | 0,89  | 1,00        | 0,74  | 0,89            | 0,82  | 0,72 |
| \( P \)           | 0,83          | 0,84  | 0,74        | 1,00  | 0,92            | 0,20  | 0,65 |
| \( E_\omega - P \)| 0,84          | 0,92  | 0,89        | 0,93  | 1,00            | 0,93  | 0,98 |
| \( ET \)          | 0,95          | 0,74  | 0,85        | 0,78  | 0,91            | 1,00  | 0,82 |
| \( M \)           | 0,74          | 0,58  | 0,71        | 0,65  | 0,96            | 0,78  | 1,00 |
| Standard deviation | 83,0          | 178,3 | 178,0      | 57,8  | 97,9            | 77,2  | 112,0 |
| The coefficient of variation \( V \), % | 10,4 | 6,4 | 7,3 | 30,6 | 12,0 | 12,1 | 33,0 |

Analysis of the data shows that the lack of natural moisture \( (E_\omega - P) \), which characterises the heat and moisture supply of the calculated soil layer during the growing season, has a significant impact on the amount of evapotranspiration. The interrelation between evapotranspiration and potential
Evapotranspiration is the strongest, it's a complex hydrometeorological characteristic, the coefficient of variation is 0.96.

The magnitude of evapotranspiration is based on determining of the bioclimatic coefficients, as well as the characteristics of their components based on scientific and analytical studies and statistical analysis of long-term experimental data on the cultivation of summer planting potatoes in the conditions of the floodplain's Lower Don, aimed at creating new design models that ensure the rational use of water and energy resources, high productivity of potato cultivation, conservation and improvement of soil fertility, creating a favorable ecological situation in the irrigated agricultural landscape [16–22].

Data on the accumulated active temperature, the sum of the deficits in air humidity and the magnitude of evapotranspiration are presented in Table 3.

Table 3. Data on temperatures, deficit of air humidity and evapotranspiration on the main phases of the potatoes’ development for the summer planting period for the survey years under study on average

| Characteristic                        | Young growth | Budding | Blossom | Termination of foliage growth | Wilting foliage | Technical ripeness | During the growing season |
|---------------------------------------|--------------|---------|---------|-------------------------------|-----------------|--------------------|-------------------------|
| Evapotranspiration (ET), mm           | 41,4         | 109,8   | 49,6    | 78,0                          | 61,2            | 36,2               | 376,2                   |
| The sum of active temperatures (Σt), °C | 254,6        | 448,6   | 178,6   | 357,6                         | 347,0           | 213,8              | 1800,2                  |
| The amount of deficit of air humidity (Σdφ), mb | 161,1        | 330,6   | 130,9   | 267,0                         | 247,8           | 164,6              | 1335,6                  |

According to A. M. Alpatyev, linear bioclimatic patterns depending on the radiation balance (R), sums of average daily deficits of air humidity (Σdφ) and air temperature (Σt) have an accuracy of up to 90%. Currently, curvilinear dependencies are used, which allows to increase the accuracy of determining the parameters under study, but it is proposed to use several hydrometeorological characteristics to build more accurate dependencies. One-factor and multivariate correlation analysis was conducted, the reliability of the relationship between the values considered was determined to assess the closeness of the relationship between the components of the bioclimatic coefficients' formula: evapotranspiration (ET, mm), the sum of active temperatures (Σt °C) and the amounts of air humidity deficits (Σdφ, mb).

An analysis of the reliability of the connection's tightness of the characteristics under consideration showed that the temperature has a correlation coefficient of 0.88; air humidity deficit - 0.74; making it possible to characterize their connection with evapotranspiration as very close and close, respectively. It should be noted that during multifactor correlation analysis, the variation of evapotranspiration by 79% (determination (r^2) - 0.79) is related to the effect of the studied factors - the sum of active air temperatures and the sum of air humidity deficits and can be mathematically explained this data.

The dynamics of evapotranspiration value (ET, mm) change from the sum of active temperatures (Σt °C) and the amounts of air humidity deficits (Σdφ, mb) is presented in Figure 1 and dependence (1)
Figure 1. Dynamics of evapotranspiration changing which depends on temperature and humidity deficit

\[ ET = 92.183 + 0.13 \cdot \sum d_\phi - 0.573 \cdot \sum t + \left( 0.2 \cdot \sum d_\phi^2 - 0.7 \cdot \sum t \cdot \sum d_\phi + 1.6 \cdot \sum t^2 \right) \cdot 10^{-3} \]  \hspace{1cm} (1)

where \( ET \) - evapotranspiration, mm;
\( \sum t \) - the amount of air temperatures, °C;
\( \sum d_\phi \) - the amount of deficiency of air humidity, mb.

The actual value of potato evapotranspiration (\( ET \)) is determined by determining the elements of the water balance equation of the irrigated field according to:

\[ ET = K_{\omega} \cdot E_{\omega} \cdot K_0, \]  \hspace{1cm} (2)

where \( ET \) - evapotranspiration, mm;
\( K_{\omega} \) - bioclimatic coefficient;
\( E_{\omega} \) - potential evapotranspiration, the value of which is obtained from the weather station, mm;
\( K_0 \) - microclimatic coefficient taking into account the change of microclimate of an agricultural field under the influence of irrigation.

For the conditions of the Lower Don's floodplain as a whole for the irrigated area under consideration \( K_0 = 0.87 \).

Bioclimatic coefficients of potatoes are determined by the empirical equations of the authors depending on the biological characteristics of potato plants and the effect of actual moisture reserves in the calculated soil layer, taking into account the development phases. The equations have a general form:

\[ K_{\omega} = A_1 \left( \frac{W_H + W_K}{2 \cdot W_{HB}} \right)^2 + A_2 \left( \frac{W_H + W_K}{2 \cdot W_{HB}} \right) + A_0, \]  \hspace{1cm} (3)
where $K$ - bioclimatic coefficient;

$A_1, A_2, A_0$ - equation parameters;

$W_H, W_K, W_{HB}$ - moisture reserves in the calculated soil layer: initial, final, and at a humidity corresponding to the lowest water capacity.

The parameters of equation (4) for the various phases of growth and development of plants of the potato are given in Table 4.

An evaporator is installed to determine the amount of evapotranspiration in time in the crop rotation area, the indications of which are compared with the corresponding data of the nearest meteorological station. In the absence of evaporators, the magnitude of potential evapotranspiration is determined by regional dependencies on bridges, which are obtained by the authors as a result of modifying the model of V. P. Ostapchik, which is based on the data of weather stations in the Rostov region:

$$E_{\phi} = A \cdot (d_\phi)^h,$$

where $A, b$ - empirical parameters which are obtained by the authors for the conditions of the Lower Don's floodplain. $A = 1,220; b = 0,003; R^2 = 0,84;

$d_\phi$ - deficiency of air humidity, mbar;

$t$ - air temperature, °C.

**Table 4. Parameters of the equation for determining the bioclimatic coefficient for different phases of potato development**

| Growth and development phases | Equation parameter $A_1$ | Equation parameter $A_2$ | Equation parameter $A_3$ | Approximation reliability |
|------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Young growth                 | -0,114                   | 1,747                    | 0,025                    | 0,98                     |
| Budding                      | -0,068                   | 0,229                    | 0,601                    | 0,97                     |
| Blossom                      | -0,082                   | 0,605                    | 0,672                    | 0,99                     |
| Termination of foliage growth| -0,073                   | 0,550                    | 1,395                    | 0,97                     |
| Wilting foliage              | -0,295                   | 0,741                    | 1,027                    | 0,96                     |
| Technical ripeness           | -0,027                   | 0,181                    | 0,645                    | 0,92                     |

The performed experiments and the obtained data allowed us to establish a complex empirical relationship that allows us to determine the actual moisture reserves of the soil in the conditions of the Lower Don's floodplain:

$$ET = 92,183 + 0,13 \cdot \sum d_\phi - 0,573 \cdot \sum t + (0,2 \cdot \sum d_\phi^2 - 0,7 \cdot \sum t \cdot \sum d_\phi + 1,6 \cdot \sum t^2) \cdot 10^{-3} =$$

$$= \left( A_1 \frac{W_H + W_K}{2 \cdot W_{HB}} \right)^2 + A_2 \left( \frac{W_H + W_K}{2 \cdot W_{HB}} \right) + A_0 \cdot 1,22 \cdot d_\phi^{0,003 \cdot t} \cdot 0,87$$

so, we get:

$$92,183 + 0,13 \cdot \sum d_\phi - 0,573 \cdot \sum t +$$

$$+ \left( 0,2 \cdot \sum d_\phi^2 - 0,7 \cdot \sum t \cdot \sum d_\phi + 1,6 \cdot \sum t^2 \right) \cdot 10^{-3} = 1,0614 \cdot d_\phi^{0,003 \cdot t}.$$
The deviations of the actual values of meteorological parameters from their mean multiyear values should be used to improve the accuracy of the calculation of the evapotranspiration of the irrigated field. Deviations of potential evapotranspiration and evapotranspiration from their mean multiyear values, according to the corresponding weather stations and experimental results, are calculated by the following modular coefficients:

\[ K_{\Delta E} = \frac{E_{\omega}}{E_{\omega}}, \quad (7) \]

\[ K_{\Delta ET} = \frac{ET}{ET}, \quad (8) \]

where \( K_{\Delta E} \) and \( K_{\Delta ET} \) - modular deviations of potential evapotranspiration and evapotranspiration values;

\( ET \) and \( E_{\omega} \) - actual values of evapotranspiration, potential evapotranspiration, which are obtained from weather station data, and transpiration, mm;

\( \overline{ET} \), \( \overline{E_{\omega}} \) – mean annual values of potential evapotranspiration and evapotranspiration, mm.

- Based on the analysis of experimental and average annual data, a nonlinear dependence of the relative deviations of evapotranspiration on potential evapotranspiration (Figure 2), which is described by a second-degree polynomial type equation, is obtained:

\[ K_{\Delta ET} = f(K_{\Delta E}) = 1,51 - \left( \frac{E_{\omega}}{E_{\omega}} \right)^2 - 1,48 \left( \frac{E_{\omega}}{E_{\omega}} \right) + 0,9, \quad (9) \]

\[ K_{\Delta ET} = f(K_{\Delta E}) = 1,51 - \left( \frac{E_{\omega}}{E_{\omega}} \right)^2 - 1,48 \left( \frac{E_{\omega}}{E_{\omega}} \right) + 0,9. \]

\[ R^2 = 0,96 \]

Figure 2. Empirical dependence of the relative deviations' dynamics of evapotranspiration on potential evapotranspiration

In order to avoid excessive accumulation of errors, it is recommended to periodically correct the values \( ET \) and \( E_{\omega} \) by comparing them with actual measurement data on a specific field. Such measurements should be carried out 1-2 times during the growing season.

4. Findings
The conducted multifactor correlation analysis allows us to conclude that the variation of the evapotranspiration rate by 79% is related to the effect of the studied factors, and the total correlation coefficient is 0.89. As a result, the empirical dependences of evapotranspiration on the sum of active air temperatures, the sum of air humidity deficits and their multifactorial dependence were obtained. Empirical dependences of bioclimatic coefficients on the actual moisture reserves in the calculated soil layer are established, and a complex empirical dependence is established on the establishment of actual soil moisture reserves.
The results of the studies allowed us to establish a significant increase in the accuracy of determining evapotranspiration and potential evapotranspiration according to the models developed in comparison with actual data, which ensured a significant increase in the efficiency of water and energy resources used in the implementation of irrigation regimes of potato plantations in the conditions of the Lower Don's floodplain.

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