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The evaluation of irrigating meliorations efficiency after the change of climatic conditions

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Abstract: The article reviews one of the important problems of water usage – operational management of irrigation. The article discusses a methodological approach to the estimation of economic efficiency of water usage in the conditions of climate change in the territory concerned. So far, there has not been a simple method to determine this indicator. When assessing climatic conditions, taking into account their influence on the productivity of agricultural crops, it is necessary to take into account meteorological factors that have a decisive influence on the development of agricultural crops and, accordingly, determine their yield. These include primarily heat and moisture. Moreover, it is necessary to take into account their possible negative influence on the development of plants, considering that for each crop a certain optimum regime of temperature and soil moisture is required in different phases of its growth. To assess climatic conditions taking into account the potential crop productivity, we can use the *CPA* formula. Calculations have shown a close relationship between the *CPA* and the yield of agricultural crops. Correlation coefficients of the obtained bonds vary from 0.85 to 0.98 depending on the culture and the territory.

Keywords: irrigation, meliorations, natural resource potential of the territory, water use efficiency, winter wheat

INTRODUCTION

In conditions of changing climatic conditions [Gernaat *et al.* 2021; Jackson 2021; Romashchenko *et al.* 2021], the cultivation of agricultural products on irrigated lands has great importance to intensify agricultural production. A steady growth of the production is determined by biological characteristics of an agricultural crop and climatic conditions on the territory.

In order to ensure the economically efficient use of irrigated land and stable yield of agricultural products, it is necessary to investigate the agricultural climatic resources at the territory before proceeding with water application on irrigated lands. For this reason, justification to cultivate a particular crop on irrigated land is relevant.

According to the significant variability of weather conditions in the study area and the increase in the recurrence of dry years, the study of crop productivity depending on climatic factors is relevant.

In recent decades, the scientific community around the world has paid considerable attention to climate changes at both regional and global levels. Thus, the aim of the work is to study the relationship between productivity of agrocenoses depending on the variability of weather conditions in the study area [Tkachuk, Zaporozhchenko 2017].

The scientific justification of the feasibility of growing crops on irrigated lands necessitates the examination of two aspects. The first aspect is to determine the economic dimension of cultivating a crop with irrigation, whereas the second is to determine the order of irrigation of agricultural crops when the climatic conditions change during the vegetation period. The first aspect should be considered in relation to the cost of necessary resources (water, seed, fertilisers, etc.) to determine the value of products, and the second should be considered for determining an economically justified irrigation order to increase the yield. Since the key issue is the irrigation order, it is important to adapt irrigation regimes in accordance with changes of climatic conditions to obtain sustainable crop yields.

MATERIALS AND METHODS

The melioration practice includes many methods for calculating the irrigation order in particular years. These methods include the graphic analytic method by Kostyakov, the bioclimatic method by A.M. Alpatyev and S.M. Alpatyev, improved bioclimatic method by Ostapchik, biophysical method by Shtojko, complex method by Kharchenko, method of FAO PM (Penman–Monteith), agro-hydrometeorological method of the Dnipro State University of Agriculture and Economics, and others [ALPATYEV 1973; KHARCHENKO 1975, KOSTYAKOV 1933, LYTOVCHENKO 2011; MONTEITH 1965, PENMAN 1948; SHTOYKO 1965]. These methods apply water balance equations and differ only by the determining of individual components. These methods determine total evaporation (water consumption, evapotranspiration). To do this, empirical formulas proposed by Blaney and Kriddle, Penman, Sharov, Ivanov and others are used, as well as the radiation method and the method of evaporators [BLANEY, CRIDDLE 1950; IVANOV 1954; MONTEITH 1965; PENMAN 1948, SHAROV 1959]. However, in practical calculations, individual components in the water balance equation can be taken from different methods.

When calculating the irrigation order, the selection of the year of a given advisability is crucial. The solution to the problem of highly efficient use of water, energy, finance, labour, and other resources depends on the year chosen. The analysis of existing methods [DBN V.2.4.1-992000; LYTOVCHENKO 2011; MTD 33-04-03-93] helps to choose one of them. After all, each of them gives different results, and the calculated year is one for all the crops. In practice, this leads to an increase or decrease in irrigation norms, and consequently, the increase in the value of the final product. Methods for determining the provision of natural moisture during a year vary both in principle approaches and in data necessary for calculations. As regards principle approaches, we can focus on two of them: the shortage of water for the consumption by plants and soil moisture at an estimated date.

Regarding data, it should be noted that there are always mistakes of various nature, as well as contradictory individual measurements. Therefore, when using one or the other method, it is necessary to evaluate all information obtained as a result of calculations, different in size and in essence. For this purpose, it is advisable to apply methods based on artificial neural networks. In the presence of a certain number of observations, these methods enable to classify years under similar natural humidification of the territory, and provide a qualitative characteristic of the provision of natural resources, such as soil moisture, heat, etc.

When classifying years according to natural moisture, there is a problem of choosing the most informative criteria, as the reduction of their number often improves the quality of decision-making (and reduces cost and time to collect information). It is desirable to determine the required number of criteria and their significance (priority).

For solving this problem, the detection of "duplicate" and "noise" information is necessary. As a result, the criteria for assessing a given year includes precipitation during the growing season (mm), average soil moisture during the critical period of crop development (mm), irrigation rate, and the integrated climate indicator (ICI) [MTD 33-04-03-93]. Soil moisture reserves and irrigation rate are calculated using the agrohydrometeorological method [LYTOVCHENKO 2011]. This approach is likely to be legitimate, as statistical series of observations are limited in size and often unrepresentative. As a result, close or even identical values of a series member, selected as a criterion, will characterise different provision of natural moisture at the territory. In addition, short statistical series sometimes fail to characterise individual humidification conditions, so it is advisable to use the method of cluster analysis. It has proven efficient even when there is little data and requirements for the normality of random variables distribution and other requirements for classical statistical analysis methods are not met [JAIN, DUBES 2012; KAUFMAN, ROUSSEEUW 2007].

The article presents results of calculations pertaining to the territory adjacent to the Raivka Village, Sinelnikovo District, Dnipropetrovsk Region (Fig. 1).

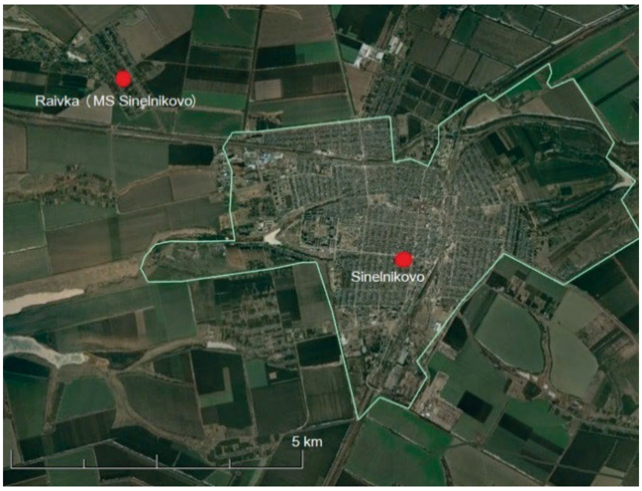

Fig. 1. Location of Raivka Village; source: own elaboration based on Google Earth

The research used information from the meteorological station located in the Raivka Village, Sinelnikovo District, Dnipropetrovsk Region (Fig. 1) and the Internet weather resource rp5 [Rp5; VNIIGMI-MTSD 1966–1987]. A representative 22-year period of 1966–1989 was adopted for the research [TKACHUK, ZAPOROZHCHENKO 2016]. It should be noted that the authors analysed the representativeness of 2005–2015 using modern data mining methods, which confirmed the correctness of the period chosen to assess the impact of weather variability on crop productivity.

When assessing the productivity of crops depending on weather conditions in specific years with sufficient accuracy for engineering calculations, we consider it appropriate to divide moisture conditions into five clusters: (supply p, %): 0–20% – very moist, 20–40% – moist, 40–60% – average, 60–80% – dry, 80–100% – very dry.

A classic way for studying the growth of crop due to irrigation is the mathematical modelling – mathematical model, algorithm, and calculation. However, in addition to classical schemes, there are methods based on fundamentally different approaches. Their idea is to avoid the creation of a comprehensive mathematical model of the object (and it often is impossible to build appropriate model), but instead answering specific questions. In this case, the answer should come from general considerations for a wide range of tasks. Studies of this kind were conducted to predict crop yields, water levels in rivers, aquifers distinction, indirect geophysical data, etc. The exact answer to these questions produces a simple form that reflects the compliance with certain conditions of natural productivity moisture levels during the growing season divided into advance classes. This task can be solved by assessing agricultural productivity.

At present there is no simple method that allows to define this indicator. While evaluating climatic conditions in view of their impact on the productivity of crops, we need to take into account meteorological factors which have a decisive influence on the development of crops and their yield. They should include heat and water, their possible negative impact on the development of plants, considering that for each crop some optimal mode of temperature and humidity of the soil in different phases of development of the agricultural culture is necessary. In the framework of the climatic conditions outlined above, considering the potential yield of crops (*CPA*, mm·hPa^{-1}), Equation (1) is as follows:

$$CPA = \frac{\sum_{i=1}^{n} t_{\text{act}} - \sum_{i=1}^{n} t_{\text{tox}}}{t_{\text{bas}}}\eta + \\ + \frac{k_w W_{100} + \sum O(0.03 + 0.97E^{-0.125N})}{0.75 k_b \sum D} 100 \quad (1)$$

The explication of Equation (1) is shown in Table 1.

Table 1. Explication of the indicators of Equation (1)

Symbol	Explanation of the symbol
CPA	potential yield of agricultural crops
$\sum_{i=1}^{n} t_{\text{act}}$	sum of active air temperatures for the calculation period (°C)
$\sum_{i=1}^{n} t_{\text{tox}}$	sum of toxic air temperatures for the calculation period (°C)
t_{bas}	basic sum of average daily air temperatures for the period of vegetation of agricultural culture (°C)
η	humidification conditions; defined as the ratio of current soil moisture to its optimal value
k_w	share of soil moisture that can be used by the plant
W_{100}	reserves of soil moisture in 0–100 cm of soil layer (mm)
O	precipitation (mm)
N	number of days from the date of transition of the average daily air temperature through +5°C (+10°C – for corn) in the spring to the settlement date
k_b	biological evaporation rate can be determined by the recommendations of Ostapchik [DBN V.2.4.1-99] or other authors
$\sum D$	sum of average daily deficits of humidity (hPa)

Source: own elaboration.

The sum of toxic air temperatures $\sum_{i=1}^{n} t_{\text{tox}}$ includes daily temperatures lower than the biological minimum for a crop and greater than 30°C.

Interpretation of the proposed indicator (*CPA*) can be defined as the intensity of moisture consumption in the 0–100 cm layer of soil.

Currently, we have several general and special purpose software solutions developed for processing observational data. These include Mathcad, Mathematic, R, and others [PTC 2007]. To process the existing data series and build Figure 2, the authors used the analytical platform Deductor 5.3.

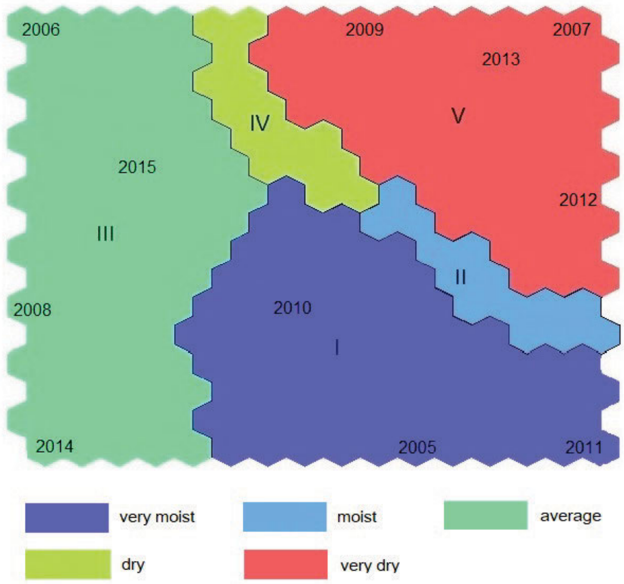

Fig. 2. Clusters of natural humidity conditions under winter wheat crops in the critical period (MS Sinelnikovo); source: own elaboration

RESULTS AND DISCUSSION

The research was conducted for leading crops. The article presents results for winter wheat.

Results (Tab. 2) confirm the expediency of the above-stated technique used to define natural humidity conditions at the investigated territory with the application of the cluster analysis method.

The analysis of Table 2 shows the absence of the first and third clusters of winter wheat natural moisture in the study area. This indicates that the retrospective series from 2005 to 2015 is not representative.

Kohonen's self-organising maps were developed to visualise data obtained (Fig. 2). Figure 2 enables to determine which year best corresponds to a particular cluster. The analysis of Figure 2 shows that such years are located both in the centre and on the periphery of the clusters. Therefore, the most appropriate year is the one closest to the centre of a particular cluster, because years located on their periphery can simultaneously characterise different humidification conditions, and therefore are not typical.

While summarising the results shown in Figure 2 and Table 2, it can be noted that the number of observations from 2005 to 2015 contain very wet, humid, and very dry years, and therefore cannot be used to assess the effectiveness of irrigation reclamation.

Given the above, a representative 22-year observation period of 1966–1989 was adopted to assess the effectiveness of irrigated land reclamation [Tkachuk, Zaporozhchenko 2016].

Table 2. The security of the year regarding natural moisture for winter wheat in 2005–2015

Year	Precipitation (mm)	Average soil moisture for the critical period (mm)	Irrigation rate (mm)	*CPA* (mm·hPa^{-1})	Cluster number
2005	183.1	211	80	0.299	0
2010	206.7	226	80	0.351	0
2011	214.4	202	80	0.312	0
2006	170.1	284	80	0.325	2
2008	229.9	254	80	0.234	2
2014	324.9	228	80	0.065	2
2015	196.8	264	80	0.364	2
2007	112.8	167	120	0.792	4
2009	104.3	235	120	0.727	4
2012	161.4	180	120	0.753	4
2013	97.0	189	120	0.779	4

Source: own study.

In a similar vein to the above method, we set groups of years under natural moisture conditions at the study area. Then, for each group, we choose a characteristic annual model. The distance to the centre of the cluster is taken as a criterion when choosing a model year of a certain security. Thus, we determined yearly probability characteristic (supply *p*, %) corresponding to certain humidification conditions. For the adopted retrospective series, very wet conditions (p = 10%) are typical for 1973, wet (p = 25%) 1977, medium (p = 50%) 1970, medium dry (p = 75%) 1979, and dry (p = 90%) 1985. For these years, according to the statistical reporting directories of the Main Department of Statistics in Dnipropetrovsk Region (Ukr. Golovnogo upravlinnya statistiki u Dnipropetrovs'kij oblasti), the average yield of winter wheat was adopted, and according to Equation (1) the *CPA* was calculated. According to these data, the dependence of winter wheat yield on the *CPA* is shown below (Fig. 3).

Figure 3 shows that there is a close relationship between the quantities under consideration. The increase in yield is the largest (+10.1 kg·ha^{-1}) with an increase in the *CPA* from 40 to 70 mm·hPa^{-1}, which corresponds to a change in moisture conditions from medium dry to wet (probability of exceeding 25–75%). Within these limits, the dependence of yield on the *CPA* is linear. An increase in yield by 0.34 Mg·ha^{-1} is observed with an increase in the *CPA* from 70 to 95 mm·hPa^{-1} (probability of exceeding 10–25%). In turn, the change of the *CPA* from 30 to 40 mm·hPa^{-1} (probability of exceeding from 75 to 90%) due to irrigation may not be cost-effective as the increase in yield is insignificant (+0.13 Mg·ha^{-1}).

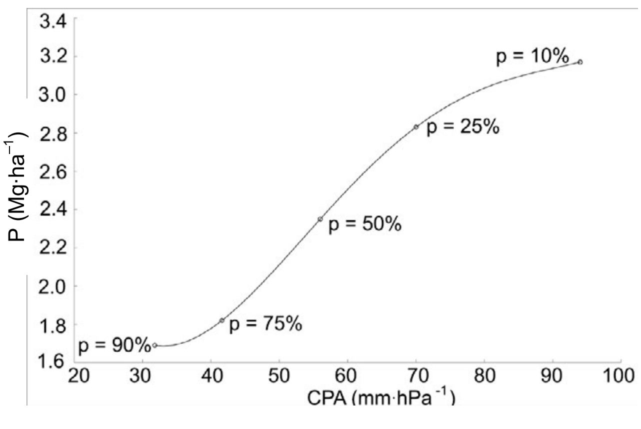

Fig. 3. Dependence of winter wheat yield (*P*) on the natural-resource potential at the territory (according to data from Sinelnikovo meteorological station); *CPA* = potential yield of agricultural crops; source: own study

Since the *CPA* rate can be artificially increased only through irrigation, the economic efficiency of irrigated land reclamation can be assessed based on the *CPA* when planning water use in different climatic conditions.

For comparison of irrigation order, calculations were made with four methods for five characteristic classes (availability). As model years are accepted as follows: for p = 10% 1973, p = 25% 1977, p = 50% 1970, p = 75% 1979, and p = 90% 1985. Results of calculations are given in Table 3.

Table 3 shows that the irrigation rates calculated using the above methods differ. Thus, the highest norms are characteristic for the advanced bioclimatic method by Ostapchik, and the lowest correspond to the agrohydrometeorological method of the DSAEU. At the same time, irrigation rates obtained using Shtoiko and Alpatyevs methods are the same. The difference in irrigation rates can be explained as follows: Ostapchik's method involves maintaining soil moisture reserves at the level of the lowest moisture content. The method of Shtoyko and Alpatyev involves maintaining soil moisture within optimal limits for crops. For example, it is maintained at a level of 75–100% of the lowest moisture content for winter wheat in the study area, i.e. within a slightly lower range. In addition, these methods give inflated results due to the imperfect definition of the water consumption deficit attributable to agricultural crops. In turn, the agrohydrometeorological method involves a fundamentally different approach to calculating norms and timing of irrigation as instead of the water consumption deficit it is based directly on the soil

Table 3. Irrigated norms of winter wheat

Method of calculation	Irrigation rate ($m^3 \cdot ha^{-1}$)	Availability of the year (%)
Bioclimatic method of A.M. Alpatyev and S.M. Alpatyev [ALPATYEV 1973]	800	10
	800	25
	1 200	50
	1 600	75
	2 000	90
Improved bioclimatic method of Ostapchyk [DBN V.2.4.1-99]	800	10
	800	25
	1 600	50
	2 400	75
	2 800	90
Biophysical method of Shtoiko [SHTOYKO 1965]	400	10
	800	25
	1 200	50
	1 600	75
	2 000	90
Agrohydrometeorological method of DSAEU [LYTOVCHENKO 2011]	400	10
	800	25
	800	50
	1 200	75
	1 600	90

Source: own study.

moisture reserves and the moisture content calculated for the soil layer of not less than the minimum allowable [TKACHUK 1999].

Thus, the use of agrohydrometeorological method for determining the timing and norms of irrigation saves water resources and reduces the negative impact of irrigation on the soil.

The most informative features in assessing the availability of natural moisture in particular years are the precipitation for the critical period of agricultural crops development and the complex climatic index [MTD 33-04-03-93]. It should be noted that the paper identifies only the informative value of data obtained to determine the year of specified security. The use of modern data mining methods enables to define the year-model for assessing climate productivity depending on humidification and to calculate irrigation needs. Calculations performed using Equation (1) show a close relationship between winter wheat yield (*P*) and the *CPA*. The use of MathCAD enabled to determine that the dependence (Fig. 3) is approximated by a third-order Equation (2):

$$P = 304 - 10.5CPA^2 - 0.00136CPA^3 \tag{2}$$

It is possible to conclude about the practical significance of analysis results pertaining to the constraint between the *CPA* and winter wheat yield based on the density and the Chaddock scale [YELISEYEVA 2007].

The correlation ratio is 0.99. On the Chaddock scale, this constraint is characterised as very high. This means that the equation can be used to determine the yield of winter wheat in order to assess the efficiency of its cultivation in different climatic conditions.

Therefore, based on the results obtained (Fig. 3), we can conclude that the most effective is the irrigated land reclamation within moisture levels ranging from wet to medium dry, which corresponds to *CPA* values from 40 to 70 $mm \cdot hPa^{-1}$.

The results of the irrigation regimes calculation show that the irrigation norms obtained by the agrometeorological method save water from 400 to 800 $m^3 \cdot ha^{-1}$ as compared to other methods. Therefore, the increase in yield per unit of water used for irrigation will be maximum when we use the agrometeorological method for calculating the irrigation regime.

CONCLUSIONS

The data presented in Figure 2 show that considering the short and non-representative series of meteorological factor observations, the cluster analysis method has significant advantages over the statistical method as it provides qualitative assessment of humidity during the year, even when there are no moisture conditions specified in the study series.

Consequently, the actual yields of agricultural crops depend not only on inter-year fluctuations in agro-meteorological conditions that occur under different humidity during a vegetation season, but also on the nature, dynamics, and intensity of changes during a particular vegetation season. Decisions to increase yield, effective use of land and natural potential of the territory, irrigation reclamation, and adaptation of agricultural technologies should start with an assessment of the natural soil moisture content. Such information can be very important while evaluating the effectiveness of irrigated land reclamation under changing climatic conditions.

Taking into account that we can only change climate performance by means of irrigation, the agricultural crop productivity should be used as a criterion for assessing the economic feasibility of irrigated land reclamation under changing climatic conditions.

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