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To cite this article: A V Tkachuk and T I Tkachuk 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1254** 012090

IOP Conf. Series: Earth and Environmental Science 1254 (2023) 012090 doi:10.1088/1755-1315/1254/1/012090

Methodology for determining the availability of natural moistening of the territory by hydrometeorological conditions for the needs of land reclamation

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Abstract. The paper considers one of the important problems of water use – determination of the humidification conditions of the territory for the hydromelioration needs. The methodical approach to determining the probability of exceeding natural moisture by a group of criteria is highlighted. Nowadays there is no single, reliable and simple method for determining this indicator. Assessing climatic conditions, considering their impact on crop productivity, it is necessary to take into account hydrometeorological factors that have a decisive influence on the development of crops and, accordingly, determine their yield. These include, first of all, precipitation, moisture reserves in the soil, evapotranspiration and other complex indicators that allow to take into account the distribution of meteorological factors during the growing season of the crop and their possible negative impact on the development of the plant, because each crop requires a certain optimal regime of soil temperature and moisture at different stages of its development. The article presents the solution of the set tasks on the example of winter wheat crops according to the data of the Dnipro meteorological station (airport).

1. Introduction

The determining factor in the development of agricultural production in the Steppe of Ukraine is natural resources, which are characterized by bioclimatic potential, soil fertility and water regime. According to FAO estimates, Ukraine has the potential for a significant (up to 3 or more times) increase in agricultural production and exports, provided that the available natural resources are used more efficiently. Insufficient level of their use is limited by a number of factors, the main of which is the natural moisture supply deficit on more than 2/3 of the territory of Ukraine.

Thus, significant variability of moisture conditions in Ukraine is the main limiting factor that limits not only the level of crop productivity, but also the use of natural and anthropogenic potential of agriculture.

Many years of agricultural experience and scientific researches show that it is possible to prevent and mitigate the negative effects of climate changing on agricultural production only with the help of irrigated land reclamation [1].

Despite thousands of years of mankind experience in irrigated agriculture, the issue of vegetative irrigation of crops has not been studied enough. The key point here is the methodology for determining the availability of natural moisture in the territory. The correct choice of the year-model in the development of the irrigation regime will prevent serious miscalculations in the design of irrigation systems, waterlogging, flooding and flooding of irrigated lands, which will inevitably lead to secondary salinization and anthropogenic soil pollution and soil degradation in irrigated areas of Ukraine.

The aim is to develop scientific approaches to environmentally safe water use aimed at preventing the growth of anthropogenic impact on the environment, ensuring environmentally safe living conditions for the population and economic activity and protection of water resources from pollution and depletion, rational use of water resources, ensuring sustainable functioning of ecosystems in the river basins of Ukraine, prevention of harmful effects of water and elimination of its consequences.

2. Literature review

The analysis of scientific and normative materials in the field of hydromelioration shows insufficient reliability of existing methods for calculating the availability of natural moisture in the territory, which are used to improve the methods of water use rationing and assessment of the complex impact of hydrometeorological factors and irrigation regimes on crop yields and the ecological condition of reclaimed lands.

It is customary to assess the natural water availability of the territory based on the amount of precipitation during the growing season, climatic indicators, crop water deficit and actual moisture content of the calculated soil layer.

The sum of precipitation is mainly used in agroclimatology to assess the moisture conditions, which is calculated as a cumulative total and graphically represented in the form of integral curves.

Lebedev studied in detail the methods of constructing the curves of availability of various climatic factors and developed a methodology for constructing nomograms of availability of precipitation amounts [2]. Any probabilistic characteristic of climate is given on the basis of analysis of a representative series of observations. The types of curves proposed by Lebedev have great stability in space, which allows them to be used for a large area, including those that do not have a representative series of observations.

Such nomograms are constructed for different territories and they can be used to estimate the availability of natural moisture in the territory. As an example, figure 1 shows such a nomogram for the South of Ukraine [3].

Assessment of the moisture availability in the territory only by the amount of precipitation is insufficient and not always objective, since each year has a specific intra-annual distribution of precipitation uncharacteristic of others. A year with long dry periods and one or two large rains can be equated to a year in which rains fell evenly throughout the growing season, although the humidity of the territory in such conditions will be different. Therefore, to exclude the peculiarities of individual years, it is advisable to consider the frequency of precipitation or take not one, but several years that are closest to the calculated availability and average their meteorological data.

The disadvantage of this method is that not only precipitation affects the humidity of the territory, but also other agrometeorological factors that are not taken into account here.

Therefore, for a more correct and objective determination of the availability of the territory's humidity, various climatic indicators are used, taking into account not only the income (precipitation) component of the water balance of the territory, but also the costs, that is, the so-called meteorological complexes. An example of the application of such systems is the methodology for selecting a year of a given availability by a complex climatic indicator (CCI),

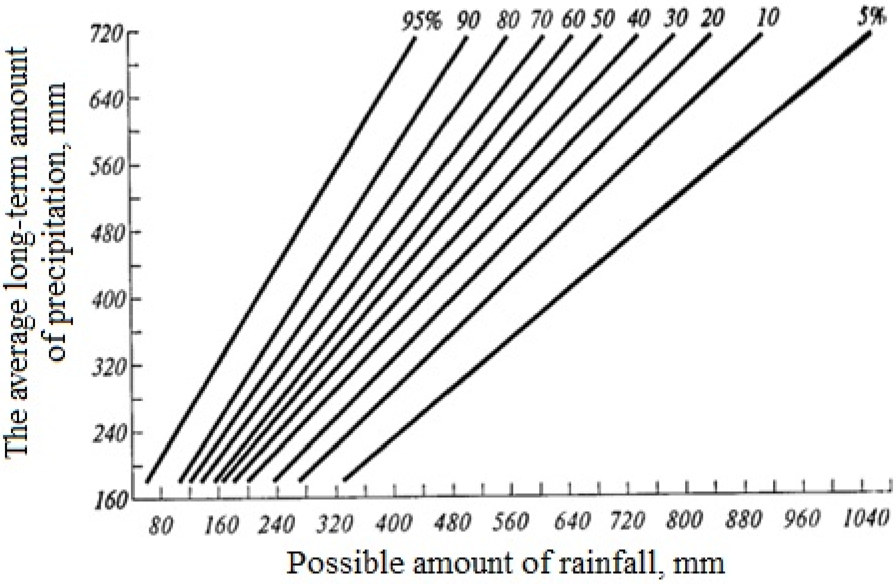

Figure 1. Graph for calculating the amount of precipitation of different availability per year (according to A. M. Lebedev) [3].

which was developed for zones of sufficient and unstable moisture in Ukraine. It is based on the availability integral indicator of CIP_j vegetation values of meteorological factors and meteorological complexes built on their basis [4–6].

The latter is determined by the formula

$$CIP_j = 1 - \frac{\sum\limits_{i=1}^{l} m_{ij}}{l \cdot n_j}, \tag{1}$$

where $\sum\limits_{i=1}^{l} m_{ij}$ – is the sum of places occupied by meteorological factors and complexes of the set $\{i\}$, $i = \overline{1, l}$ is the sum of places occupied by meteorological factors and complexes of the set, in the statistical sequences of their vegetation values for the years of observations reduced to a comparative form $\{j\}$, $j = \overline{1, n_j}$.

The value of the indicator CIP_j defined by (1), vary within $\{0;\ 1\}$ almost never reaching the limit values, which confirms the really complex and ambiguous nature of climate-forming components [6].

The choice of the year of a given availability by crop water consumption deficits by the real year method is carried out by a retrospective series of years, taking into account the composition of crops. According to this series of observations, crop water deficits are determined and their availability is calculated by the statistical method [7].

Water consumption deficits are calculated using total evaporation, which is determined by meteorological factors and biological characteristics of crops. The most widespread in Ukraine are the bioclimatic method [8, 9]; improved bioclimatic method [10]; biophysical method [11].

For a long time, the Penman [12] and Blaney-Criddle [13] methods were widespread in the world. Taking into account some inaccuracy of these methods in 1990, the FAO Council of Experts recommended to approve the combined Penman-Monteith method as a standard for calculating the reference evapotranspiration (ET_0). The method provides for the determination of ET_0 of a hypothetical crop with a height of 0.12 m, a surface resistance of $70\,\mathrm{cm}^{-1}$ and an albedo of 0.23, similar to lawn grass of the same height in the phase of active vegetation and sufficiently moistened. The Penman-Monteith equation is derived from the soil surface energy balance equation, and the dependence of ET_C on ET_0 reflects the crop coefficient K_C, which characterizes the differences between a typical agricultural crop and a reference lawn grass [14–18]. Numerous researchers have analyzed different calculation methods in different regions. As a result, the Penman-Monteith method was adopted worldwide as a standard method for determining evapotranspiration (ET_0). ET from the plant surface under non-standard conditions is given by the stress coefficient (K_S) or modification of the culture coefficient.

Probably the most objective criterion for determining the availability of natural moisture in the territory is the actual moisture reserves in the calculated soil layer. In the presence of a representative series of data on moisture reserves, their availability is also determined by generally accepted statistical methods.

Nowadays, more than 20 methods of soil moisture measurement have been developed. But all of them have certain disadvantages that limit their use – significant time discreteness and uncertain representativeness when transferring their values to other fields or arrays; some of them have low efficiency.

These shortcomings are absent in the calculation methods for determining the content of moisture reserves in the soil. They usually involve the calculation of indirect indicators of moisture content based on previous weather conditions. In some methods, a simplified water balance equation is used, considering the initial soil moisture reserves measured by instrumental methods. It should be noted that errors of instrumental measurements and calculation errors of water balance components significantly reduce the accuracy of these methods. The method of determining daily soil moisture reserves developed at the Dnipro State Agrarian and Economic University is devoid of these shortcomings [19]. Therefore, in our research, we will use this method in assessing the natural availability of the territory by soil moisture reserves.

3. Research methodology

Time series depending on the nature of the time parameter are divided into interval and momentary. When assessing the availability of natural moisture in the territory, we deal with interval series in which the value of the indicator is calculated for certain periods of time. These series correspond to flow variables. It should be noted that a series whose levels are the result of an integral series, starting from a certain defined level, is considered momentary.

In our research, we will assess the moisture availability of the territory by the amount of precipitation, complex climatic indicator, water consumption deficit and moisture reserves. All these criteria for assessing the natural moisture availability of the territory will be determined for the growing and/or critical periods of crop development.

The initial data will be meteorological data on average, maximum and minimum air temperature (^0C); atmospheric pressure at sea level (hPa); average relative humidity (%); daily precipitation (mm), air humidity deficit and average wind speed (km/h). This paper presents studies based on data from the Dnipro meteorological station (airport) for winter wheat. Meteorological data were taken from [20].

The amount of precipitation to assess the moisture conditions is calculated by accumulating their daily values for the corresponding period.

The complex climate indicator is calculated according to the recommendations set out in [4–6].

It is difficult to determine evapotranspiration in the field accurately, so it is usually calculated using empirical and semi-empirical equations. Some of them can be applied only in specific climatic conditions and cannot be used for other conditions and territories. Given that the Penman-Monteyn method is considered to be the standard method in the world, we will use it in our research.

Numerous computer programs have been created to determine ET_0 by the Penman-Monteith method. The Food and Agriculture Organization of the United Nations (FAO) recommends using the CROPWAT 8.0 program. However, the existing databases of this program (CLIMWAT, FAOCLIM) should be checked for compliance with real data and missing climatic parameters in certain periods of time. In addition, they contain only average monthly data, and there is no data on meteorological factors, soil and agroclimatic conditions and genotypic characteristics of crops grown in Ukraine. Therefore, the use of this program for the study area is impossible.

Considering the above-mentioned findings, it is advisable to use meteorological data measured at the meteorological station in the studies of natural moisture availability of the territory. Since the reference evapotranspiration (ET_0) is an indicator of climate impact, it is advisable to adopt it as a criterion for assessing the moisture availability of crops.

To calculate evapotranspiration (ET_0) we use the ET_0 Calculator Version 3.2 [21].

The choice of the year of a given availability is usually made on the basis of a retrospective series of years by ranking and determining the value of the exceedance probability. The disadvantage of this method is that the same number of years is attributed to each group of years by moisture conditions, and this is not true. After all, any series of observations contains a different number of years by moisture conditions. This drawback can be overcome by using methods based on artificial neural networks.

The analysis of the obtained results will be carried out by mathematical-statistical and cluster methods. The cluster method is used to solve the problem of classification of data obtained as a result of calculations. In addition, cluster analysis, unlike most mathematical and statistical methods, allows the distribution not by one parameter, but by several, and allows us to consider a set of input data of almost arbitrary nature.

The number of clusters is usually taken from 4 to 9 – 2-3 clusters are uninformative, and more than ten clusters are difficult to process. Therefore, in our studies, we take five clusters, each of which characterizes the moisture conditions of the year by the probability of exceeding (availability p, %): 0-20% – very wet, 20-40% – wet, 40-60% – average, 60-80% – dry, 80-100% – very dry.

Statistical multivariate cluster analysis of moisture availability of the study area will be conducted using Kohonen networks. The advantage of the network is that it is able to function in the face of interference, because the number of classes is fixed, the weights are modified slowly, and the adjustment of weights ends after training. It should be remembered that Kohonen maps offer only hypotheses about the cluster structure of the data. Therefore, for each cluster, its meaningful interpretation will be carried out using mathematical and statistical methods.

The distance to the center of the cluster is used as a criterion for the correspondence of a certain year to the humidity conditions of the territory. In this aspect, the scale becomes crucial in cluster analysis, because due to the heterogeneity of the features measurement units it becomes impossible to correctly calculate the distances between points. This problem is solved by preliminary standardization of variables.

To process the obtained calculations, the computer programs Mathcad and Deductor Studio were used [22].

4. Results and discussion

The table 1 shows the data on the calculation of the probability of exceedance separately for each of the adopted criteria using the mathematical and statistical method. To do this, the retrospective series were ranked separately for each criterion, and then the security of each member of the ranked series was calculated.

The analysis of table 1 shows that when choosing a year of a certain availability according to different criteria, the calculated real years, which characterize the moisture conditions of the

Table 1. Provision of the year by natural moisture of winter wheat crops.

Year	BCC	Year	ETo, mm/day	Year	P, mm	Year	W_{100}, mm	p, %	Humidification conditions
2021	0.938	2002	180.7	2014	286	2021	269.5	4.17	very wet
2001	0.863	2004	182.8	2021	285	2004	264.1	8.33	(p = 0-20%)
2004	0.820	2001	183.1	2004	253	2006	261.0	12.50	–
2014	0.776	2021	196.0	2001	241	2016	259.0	16.67	–
2016	0.720	2000	203.4	2016	219	2008	250.8	20.83	moist
2006	0.702	2022	204.6	2015	169	2001	250.4	25.00	(p=21-40%)
2015	0.702	2003	206.4	2011	168	2010	249.3	29.17	–
2008	0.677	2006	206.7	2017	158	2015	249.0	33.33	–
2011	0.571	2015	207.3	2000	155	2014	245.4	37.50	–
2017	0.559	2008	207.4	2008	155	2005	241.0	41.67	average
2005	0.516	2020	207.8	2006	150	2011	238.7	45.83	(p=40 – 60%)
2000	0.503	2017	210.0	2005	140	2000	238.7	50.00	–
2010	0.460	2016	211.1	2010	136	2002	237.9	54.17	–
2020	0.410	2014	213.9	2020	126	2017	237.4	58.33	–
2022	0.329	2005	222.2	2022	106	2018	233.1	62.50	medium dry
2019	0.292	2009	224.5	2019	103	2009	232.5	66.67	(p = 60-80 %)
2003	0.248	2011	227.1	2018	99	2019	229.2	70.83	–
2002	0.180	2010	228.8	2007	94	2022	226.6	75.00	–
2007	0.180	2019	234.2	2012	92	2003	220.2	79.17	–
2009	0.174	2007	237.8	2003	87	2013	217.4	83.33	dry
2012	0.149	2018	239.2	2009	72	2012	209.2	87.50	(p=80-100 %)
2018	0.118	2013	249.1	2002	65	2020	207.8	91.67	–
2013	0.112	2012	252.3	2013	55	2007	191.6	95.83	–

year by the probability of exceeding, do not coincide.

Thus, there is no clear answer as to which of the years should be taken as a model year. Therefore, in order to minimize internal differences between the evaluation criteria in each of the 5 groups that characterize the moisture conditions of the year by the probability of exceeding (provision p, %) and at the same time maximize the differences between the groups, we will use the cluster analysis method for the data presented in table 1.

The table 2 shows the main result of the cluster analysis in the form of a cluster number and a list of years belonging to each cluster. As additional information, the table contains the distance from the object to the center of the cluster. It will help to understand which of the years most closely corresponds to the moisture conditions.

The analysis of table 2 shows that the number of years in the clusters is different. Therefore, the determination of the probability of exceedance (p, %) by the conventional ranking is illegal.

Thus, the assessment of moisture conditions of the year can be carried out not by the quantitative criterion, but by the qualitative one. Since during the cluster analysis the entire retrospective series was divided into 5 clusters, the probability of exceeding (p, %) of each cluster can be estimated as the average of the established limits.

To visualize the data in table 2, we use Kohonen maps (Self-Organizing Map, SOM) (figure 2). The principle of building Kohonen maps is that in the process of training the model, neurons on the Kohonen map compete with each other for the right to best match the input data. This principle of competition and matching allows you to create a map that reflects the data structure of the original space in a lower-dimensional space. This facilitates further data analysis

Table 2. Distribution of years by moisture conditions into clusters.

Year	Cluster number	Distance to the cluster center	Humidification conditions
2001	0	0.2605	very wet
2004	0	0.2571	(p = 0-20%)
2014	0	0.2356	-
2016	0	0.2297	-
2021	0	0.2773	-
2000	1	0.1991	moist
2006	1	0.1974	(p=21-40%)
2008	1	0.0773	-
2015	1	0.0773	-
2017	1	0.1539	-
2007	2	0.3663	average
2009	2	0.2313	(p=41-60%)
2012	2	0.2677	-
2013	2	0.2375	-
2013	2	0.1960	-
2019	2	0.1927	-
2002	3	0.4593	medium dry
2003	3	0.1237	(p=61-80 %)
2020	3	0.2255	-
2022	3	0.0624	-
2005	4	0.0500	dry
2010	4	0.1147	(p=81-100%)
2011	4	0.1494	−

and visualization. The process of building a Kohonen map can be reduced to the following main stages: initialization; model training; successive iterations; end of training and mapping itself.

To evaluate the accuracy of Kohonen mapping, the mapping error is used as a metric. It occurs when SOM is trained on a large data set. This error measures the distance between the values obtained by SOM and the actual data values. Kohonen maps are considered to be highly accurate if this error does not exceed 0.1. In our research, we used the Deductor 5.3 analytical platform to build the Kohonen map and found an error of 0.01.

The analysis of figure 2 shows that the size of the clusters is different and the years are not evenly spaced. The cluster size is defined by its radius or standard deviation of the year for a particular cluster. A year belongs to a cluster if the distance from the location of the year in the cluster to the center of the cluster is less than its radius. In cases where this condition is met for two or more clusters, the year is controversial, that is, according to some of the selected criteria it can be attributed to several clusters. Therefore, in order to eliminate such ambiguities, the final choice of the year characterizing the established moisture conditions is made by the distance to the cluster center.

Consequently, the year with the minimum distance to the cluster cent is taken as the model year. In the calculations presented in this paper, we assume that for winter wheat a very wet year is 2016, a wet year is 2008, an average year is 2019, an average dry year is 2003, and a dry year is 2005.

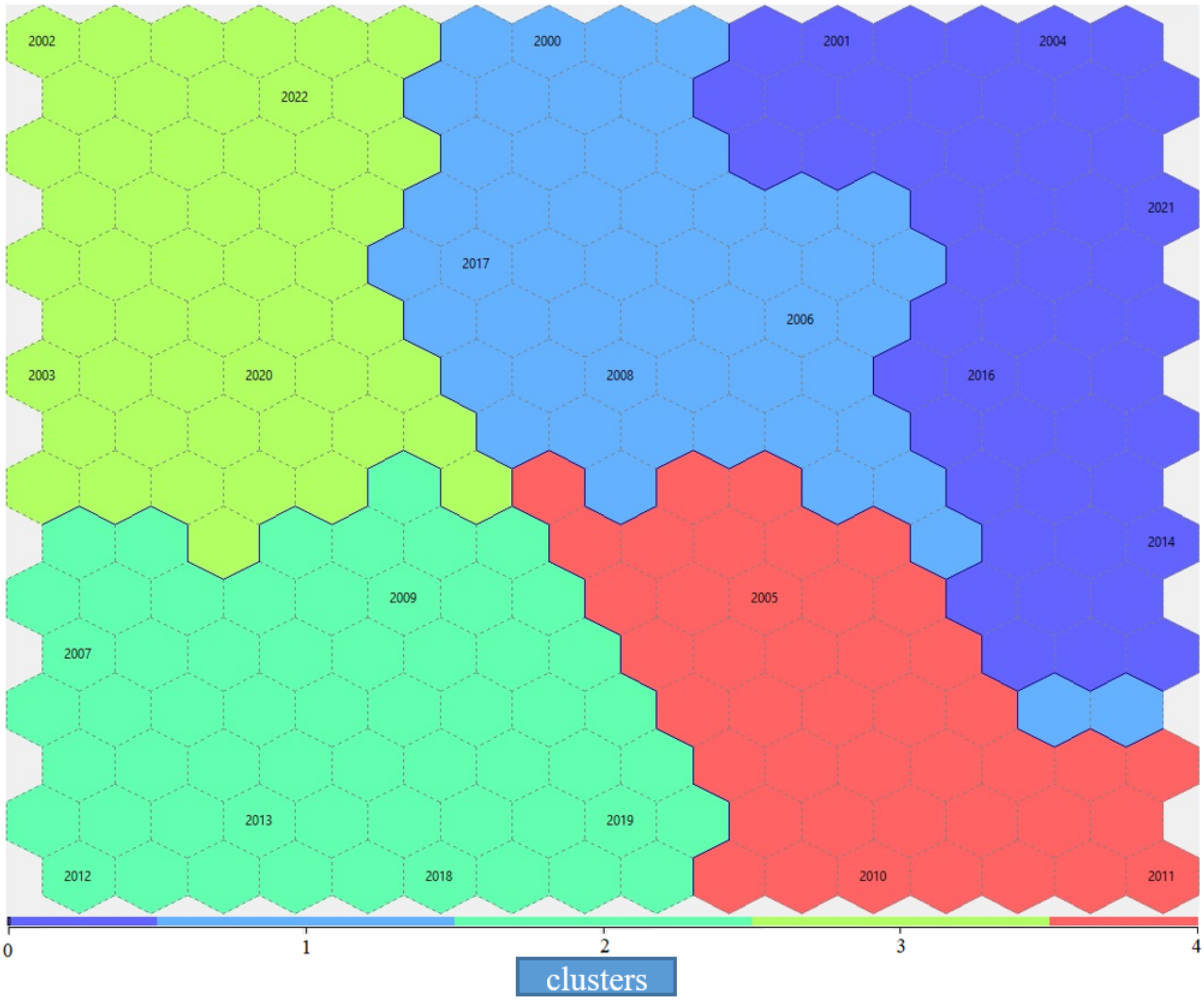

Figure 2. Distribution of years in clusters.

5. Conclusions

The data shown in table 1, table 2 and figure 2 indicate that when assessing the natural conditions of the territory based on hydrometeorological data, the cluster analysis method has significant advantages over the statistical one, as it gives a clear answer to which of the available retrospective years most accurately characterizes the moisture conditions of the territory. This is due to the consideration of several criteria. Assessment of natural moisture availability of the territory by several criteria allows to characterize the dynamics and intensity of changes in hydromelioration factors during the growing season of crops.

In the context of global climate change, the problem of availability and use of water resources is exacerbated, and the use of the proposed methodology for determining the moisture availability of the territory makes it possible to more accurately determine the need for water during hydro-amelioration measures. That is why it is advisable to choose the calculation year according to several criteria using the cluster analysis method.

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