Dynamics of the Variability of Heat and Moisture Supply Indicators and Irrigation Norms in the Conditions of the Astrakhan Region

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Abstract. During the scientific researches, scientific and methodological recommendations have been developed for determining the irrigation norms of crops for years with different water balance deficit availability, including a method for assessing and zoning a territory according to the coefficient of natural heat and moisture supply (moisture index) M_i , calculation models for rationing irrigation taking into account territorial and temporal variability, irrigation requirements for main crops, differentiated by natural and climatic zones within the Astrakhan Region. Based on statistical research and mathematical analysis of the main climatic indicators - air temperature and precipitation, trends and the degree of change in these indicators were investigated and identified according to observation data, as well as rational ecologically balanced regimes of irrigation of crops in the Astrakhan Region were calculated. According to the research results, based on the developed methodology, net irrigation requirements (mm) were calculated for the main forage and vegetable crops in years of different humidity (supply), taking into account the climatic zones identified by the moisture index (M_i) in the Astrakhan Region.

1 Introduction

The most important global problem is the intense increase in demand for water, which threatens global development in the face of uncertainty and the risk of reduced water resources associated with growing demand for food, high rates of urbanization, and climate change, which negatively affect the world's freshwater supplies. Due to the growing shortage of water resources, ensuring availability and rational use of water resources is one of the Sustainable Development Goals adopted by the UN General Assembly as part of the 2030 Agenda.[1].

According to research by Roshydromet, global warming is happening 2.5 times faster in Russia than the average on the planet.[2] The average annual air temperature in 2019 exceeded the norm (the average temperature in 1961-1990) by 2.07 °C. In Russia, it becomes warmer by 0.47 °C over 10 years, while the world average is 0.18 °C. Due to an unfavorable combination of hydrometeorological factors, in terms of an increase in temperatures with a

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decrease in precipitation, due to an increase in climate aridity, the southern regions of Russia may suffer a drop in grain yield, which may exceed 20%, especially since there is a parallel trend of deterioration in water supply and a growing shortage of water resources. Irrigated land is one of the main factors in ensuring the stability of agricultural production and ensuring food security. The output from an irrigated hectare is 2 - 5 times higher than from a rainfed one, and labor productivity, the efficiency of using natural, material, and technical resources, including fertilizers, increasing by 2 - 3 times. Reclaimed land, which is less than 8.0 % of the arable land, produces 50 percent of vegetables and up to 20 percent of feed and all rice.

World and domestic experience of scientific and industrial activities in the field of land reclamation and water management shows that the rational use of water provides not only high economic efficiency of irrigation but also its environmental safety [4,5,6]. The analysis of foreign and domestic scientific and technical materials proves that by improving the methodology for planned water use, the efficiency of irrigation can be increased by 40...50%, therefore the main task in the operation of irrigation and drainage systems is the accurate regulation of water consumption for crops and rational management of water resources during irrigation [7,8,9,10].

Therefore, an urgent task is to increase the efficiency of water resources management based on the improvement of computer information systems through the development of models for the regulation of water consumption, taking into account the probabilistic and nonlinear nature of the processes occurring in agrobiocenoses, the regularities of the cyclic process of the variability of hydrometeorological factors.

2 Purpose of scientific research

Methodological substantiation and calculation of irrigation norms for crops differentiated by natural and climatic zones of the Astrakhan Region considering environmental requirements.

3 Materials and research methods

Scientific research was carried out based on the study of scientific, methodological, regulatory, and technical materials available in the public domain, online resources, periodic domestic and foreign publications, reports on research work for a retrospective period of at least 20 years, the results of the FSBI "Upravleniye Astrakhanmeliovodkhoz" production activities for planning water use, rationing of irrigation and systemic water distribution. The tendencies and dynamics of changes in climatic indicators were found investigated according to the observational data for 1980 - 2020 on the meteorological stations of the Astrakhan Region based on mathematical analysis [2]. For each year of the long-term series, the meteorological stations were used to determine the sums of average monthly air temperatures and the sum of precipitation by months, their average values for the period from April to October, in which the vegetation of the main irrigated crops fits. The regularity of the dynamics of each climatic indicator was established using the integral method of dynamic modeling, reflecting the trend and the degree of its change for the calculated period [4].

Agroclimatic potential and irrigation requirements were calculated using the proprietary methodology of the All-Russian Research Institute Raduga, computer programs, and a database:

Calculation of irrigation regimes for crops and design standards for water demand. Methodological guidelines. Kolonna: FSBSI All-Russian Research Institute Raduga, OOO Inlight - 2012.

Planning of water use for irrigation of agricultural crops. M: FSBSI Rosinformagrotech, 2014.

ROCK.xls "Calculation of parameters of crop irrigation regimes". Official registration certificate of computer programs No. 2004610996 dated April 22, 2004;

Raduga Irrigation "Calculation of the dynamics of agroclimatic resources and their regulation" Certificate of state registration of computer programs No. 2009610137 dated January 11, 2009

4 Findings and discussion

According to the data of meteorological stations of the Astrakhan Region, long-term series of meteorological data were formed and trends in temperature and precipitation changes for 1980-2020 were built (Figure 1).

According to the Kharabali meteorological station in the Astrakhan Region, it was found that it is possible to distinguish years with a maximum air temperature 1986, 1991, 1995, 2010 in the long-term series of meteorological data with a frequency of 5 years and maximum average temperatures (20.2 °C; 20.1°C; 20.8°C; 22.2°C), respectively for the period from April to September, and over the past 10 years, the frequency of years with maximum temperatures has been increasing, which was observed in 2005, 2006, 2007, as well as in 2012, 2013, 2014 and 2020. (Figure 1).

Fig. 1. Dynamics of temporal variability of the decade mean air temperatures and precipitation amounts, for the period from April to September 1980-2020.

Analyzing the meteorological data for the Astrakhan Region in a long-term series of data from 1980–2020, as well as temperature and precipitation data for the vegetation period 2018, 2019, 2020, a tendency to an increase in the sum of maximum temperatures and a decrease in precipitation is established, which increases anomalous deviations in this territory and is reflected in figures, which will affect the increase in irrigation requirements for irrigation of crops in the Astrakhan Region.

Thus, the maximum amplitudes observed in July of 2010, 2011, 2018, 2020 were 29.0-29.1°C, maximum amplitudes in June of 2010, 2012, 2015, 2019, 2020 were 26.1-27.2°C, maximum values in August of 2017, 2016, 2014, 2010, 2007, 2006 were 27.0-28.1°C, which confirms the trend towards an increase in climate aridity in the last 10-15 years.

Fig. 2. An increasing trend in air temperature during the vegetation period according to the Kharabali meteorological station for 2020.

An ambiguous picture is observed in these months with the amount of precipitation. So the average annual value of the amount of precipitation for the vegetation period is 166 mm. However, there is a consistent pattern for decreasing precipitation. 218 mm were recorded in 2009, 14.9 mm were recorded in 2016, and in 2020 precipitation was 66.7 mm.

The minimum amount of precipitation falls in June-August. Thus, no precipitation was recorded from March to July of 2016, it was 3.3 mm and 11.6 mm in August and September respectively. The lowest precipitation values (0.3-0.5 mm) in July were noted in 2011, 2020, in August the minimum precipitation was noted in 2010, 2015, 2017, 2018. This reflects in the moisture supply decrease of the territory and the productivity of crops (Figures 4 and 5).

Fig. 3. The dynamics of precipitation changes during the vegetation period according to the Kharabali meteorological station for 2020.

Data from three Zelenga meteorological stations. Khabarali and Cherny Yar of the Astrakhan Region (Southern FD) were used to assess the evaporation, heat, and water supply of the territory, and further calculate the irrigation parameters for crops (Figures 4 and 5). Over the past 10 years, humid years have been identified with a provision of 5% and 25% with a moisture index (M_i 0.37-0.28) - 2009, with an average moisture supply of 50% - 2010, 2012 with (K_u 0.22-0.20), and medium dry 75% - 85% 2014, 2017, 2019 with (M_i = 0.18-0.15), dry 95% supply with (M_i = 0.14-0, 09) is 2015, 2016, 2018, 2020.

Fig. 4. Evaporation typical for the Astrakhan Region (according to the data from the Zelenga, Kharabali, Chernv Yar meteorological stations).

Fig. 5. The typical humidification coefficient for the Astrakhan Region (according to the data from the Zelenga, Kharabali, Chernv Yar meteorological stations).

The assessment of the heat and moisture supply coefficient shows that in recent years there has been a tendency towards a stable decrease in the heat and moisture supply coefficient and the frequency of years with insufficient precipitation, which can lead to a change in the natural and climatic zone from dry steppe to semidesert. Also, the decreasing dynamics in the coefficient of heat and moisture supply leads to an increase in the total water consumption for crops.

During the scientific researches, a scientific and methodological document has been developed for determining the irrigation norms of crops for years with different water balance deficit availability, including a method for assessing and zoning a territory according to the coefficient of natural heat and moisture supply K_u , calculation models for rationing irrigation taking into account territorial and temporal variability, irrigation requirements for main crops, differentiated by natural and climatic zones within the Astrakhan Region (Figure 6).

Fig. 6. Flowchart and algorithm for calculating the water consumption deficit.

The tendency of the variability of irrigation norms deficits depending on moisture supply, with differentiation by natural and climatic zones, is shown in Tables 1-3. The variability of irrigation norms by territory and time necessitates a differentiated approach to the choice of the year of the calculated irrigation provision and the development of irrigation regimes according to a specific zone and year of moisturizing. At the same time, a significant role is

assigned to the position and dynamics of groundwater, their part in the water balance of the soil and root zone.

Table 1. Environmentally friendly irrigation norms (mm) calculated based on average annual data from Zelenga meteorological station ($M_i = 0.25$).

Crop	Probabilistic (secured) values of the net irrigation requirement at P% supply, mm			
	25%	50%	75%	95%
Winter crops	120	135	170	220
spring crops	140	180	220	250
late potatoes	210	260	310	350
early potatoes	120	160	190	220
grain maize	220	310	400	450
maize for silage	160	230	350	410
fodder beet	154	210	280	280
beetroot	190	220	320	370
past alfalfa	314	350	421	472
annual herbs	230	270	320	360
late cabbage	230	310	360	420
early cabbage	150	230	260	350
vegetables (tomatoes)	280	330	380	430
vegetables (carrots)	220	280	320	380
vegetables (onions)	180	230	290	330
melon (watermelon)	260	320	380	450
fruit-bearing garden (apple, pear, cherry, apricot)	240	300	360	400
grapes	180	230	320	380

Table 2. Environmentally friendly irrigation norms (mm) calculated based on average annual data from Kharabali meteorological station ($K_u = 0.22$)

Crop	Probabilistic (secured) values of the net irrigation requirement at P% supply, mm			
	25%	50%	75%	95%
winter crops	140	180	220	260
spring crops	160	210	280	300
late potatoes	220	270	340	380
Early potatoes	140	180	230	270
grain maize	270	350	420	480
maize for silage	248	310	390	430
fodder beet	200	230	325	340
beetroot	210	250	350	390
past alfalfa	350	420	470	530
annual herbs	270	320	380	430
late cabbage	280	370	400	450
early cabbage	200	270	320	390
vegetables (tomatoes)	295	350	410	474
vegetables (carrots)	250	310	370	410
vegetables (onions)	210	250	320	350

Continuation of table 2

Melon (watermelon)	290	380	440	510
Fruit-bearing garden (apple, pear, cherry, apricot)	270	330	400	450
Grapes	280	320	410	480

Table 3. Environmentally friendly irrigation norms (mm) calculated based on average annual data from Cherny Yar meteorological station (Ku = 0.20).

Crop	Probabilistic (secured) values of the net irrigation requirement at P% supply, mm			
	25%	50%	75%	95%
winter crops	180	200	240	290
spring crops	200	240	280	320
late potatoes	220	290	350	390
early potatoes	150	200	240	280
grain maize	290	370	450	505
maize for silage	260	330	400	450
fodder beet	220	250	340	395
beetroot	231	290	370	420
past alfalfa	400	470	530	610
annual herbs	305	344	386	429
late cabbage	300	390	425	480
early cabbage	210	280	330	410
vegetables (tomatoes)	310	370	440	510
vegetables (carrots)	274	320	390	430
vegetables (onions)	225	280	345	380
watermelon	320	400	510	570
fruit-bearing garden (apple, pear, cherry, apricot)	290	385	430	490
grapes	310	360	420	460

Environmentally friendly irrigation norms for crops in various natural landscapes for 75% of the availability of the year are presented in Table 4.

Table 4. Environmentally friendly irrigation norms (net) of crops for the Astrakhan Region 75% of the supply during sprinkling irrigation

Crop	Irrigation requirement, m3/ha 75% supply					
	Delta (Zelenga meteorological station)	Floodplain at the level of groundwater occurrence (Khabarali meteorological station)				Steppe (Cherny Yar meteorological station)
		1.0 - 1.5 m	1.5 - 2.0 m	2.0 - 2.5 m	> 3.0 m	
Winter crops	1700	1450	1700	2000	2200	2400
Spring crops	2200	1848	2156	2492	2800	2800
Late potatoes	3100	2482	2924	3162	3400	3500
Early potatoes	1900	1679	1978	2139	2300	2400
Grain maize	4000	3200	3680	4400	4200	4500
Maize for silage	3500	2574	3000	3471	3900	4000
Fodder beet	2800	2145	2502	2892	3250	3400
Beetroot	3200	2310	2695	3115	3500	3700
Past alfalfa	4210	3100	3619	4183	4700	5300
Annual herbs	3200	2508	2936	3380	3800	3860
Late cabbage	3600	2640	3080	3560	4000	4250
Early cabbage	2600	2112	2464	2848	3200	3300
Vegetables (tomatoes, peppers, eggplants)	3800	3000	3526	3810	4100	4400
Vegetables (carrots)	3200	3219	3515	3626	3700	3900
Vegetables (onions)	2900	2784	3040	3136	3200	3450
Watermelon	3800	2900	3390	3916	4400	5100
Fruit-bearing garden (apple, pear, cherry, apricot)	3600	2640	3070	3560	4000	4300 5300
Grapes	3200	2706	3157	3649	4100	4200

Based on the research results, the dependences of the change in $\Delta Y_i = 1 - Y_i/Y_{max}$ were built - the relative decrease in yield in shares of the yield value, due to the change in $\Delta \ell_{vi}$ of the relative decrease in water supply (Table 5).

The elements of the equation are defined as follows:

$$\Delta \ell_{vi} = 1 - \frac{E_{vi}}{E_{vopt}}$$

(1)

where: $\Delta \ell_{vi}$ - the relative decrease in water supply (actual water consumption) of the crop in shares of E_{vopt} ,

E_{vopt} - optimal water consumption at optimal water regime of the soil and the level of the plants' water supply, mm;

E_{vi} - water consumption at the actual plants' water supply, in a specific vegetation period, mm.

Table 5. Equations of connection between the relative decrease in yield and a decrease in the natural water supply of the vegetation period of crops.

Crop	Equations of connection $\Delta Yi = f(\Delta \ell_{vi})$
Winter wheat	$\Delta Yi = -0.003 + 0.63\Delta \ell_{vi} + 0.77\Delta \ell_{vi}^2$
Alfalfa for hay	$\Delta Yi = -0.002 + 0.33\Delta \ell_{vi} + 1.07\Delta \ell_{vi}^2$
Sugar beet	$\Delta Yi = -0.0019 + 0.45\Delta \ell_{vi} + 0.75\Delta \ell_{vi}^2$
Maize for silage	$\Delta Yi = -0.026 + 0.64\Delta \ell_{vi} + 0.86\Delta \ell_{vi}^2$
Late cabbage	$\Delta Yi = -0.024 + 1.08\Delta \ell_{vi} + 0.36\Delta \ell_{vi}^2$
Late potatoes	$\Delta Yi = -0.025 + 0.91\Delta \ell_{vi} + 0.45\Delta \ell_{vi}^2$

Using the obtained equations of connection, it is possible to establish the relative and absolute values of the decrease in yield from the lack of water supply (water consumption deficit) of crops cultivated in the region. Depending on the availability of precipitation, natural moisturizing has a significant impact on the value of the crop yield. In dry and very arid zones, the crop yield decreases to almost zero as the deficit in rainfall increases. When predicting the crop yield in arid natural and climatic zones, it is important to take into account the influence of the moisture supply of the vegetation period when rationing irrigation, since one of the main limiting factors in the process of plant growth and development is moisture supply.

5 Conclusion

In terms of moisture supply, two main agroclimatic regions can be distinguished In the Astrakhan Region: - very dry, which includes Krasnoyarsk, Volodarsky, and Kamyzyaksky districts, and dry, which includes the rest of the region. As a result of the research work, rationing of irrigation was carried out using the water balance method, the dynamics of the elements of which is determined by a large number of stochastic hydrometeorological factors. Elements such as evapotranspiration, precipitation, soil moisture reserves vary significantly in space and time, and their variability, in turn, has a strong effect on the irrigation regime and crop yields. The proposed method for calculating irrigation norms for crops makes it possible to assess the bioclimatic potential and prospects for the development of hydro amelioration, substantiate the feasibility and efficiency of irrigation development, the choice of the structure of crop rotations, and the most valuable crops for cultivation on irrigated lands, to optimize the design irrigation regimes and technical and operational parameters of irrigation systems. The recommended irrigation requirements for the conditions of the Astrakhan Region are ecologically friendly considering the difficult soil and climatic conditions of the Astrakhan Region, soil salinity, depth, and mineralization of groundwater. These studies made it possible to reveal the reaction of various crops to the lack (deficiency) of natural moisture and to determine design norms and irrigation regimes for a number of crops cultivated in the region.

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