Analysis of Water Resources in the Arid Region of Saratov Oblast Based on Satellite Information

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Abstract— The problem of water supply in arid regions is still topical and needs to be studied. The aim of the study was to develop a program for the analysis of the dynamics of water resources from the satellite images of the Saratov region. The analysis of the images made it possible to create a program for calculation of the water surface area of the water bodies used for estimation of the water reserves dynamics depending on climatic and anthropogenic factors from 2007 to 2022. The water bodies located in the most arid area of the arid region of Saratov region and used by the population for household and drinking water supply were investigated in the work. The results showed a direct marked relationship between the volumes of spring water supply and precipitation. Also revealed a direct high correlation between the reduction of water reserves in summer and the volume of precipitation from May to August. The program and revealed regularities can be used for estimation of water reserves in artificial lakes and rivers of arid regions.

*Keywords***:** arid region, water supply, satellite images, precipitation.

1. INTRODUCTION

At present, the problem of water supply in arid regions is quite acute and does not lose its relevance [1, 6]. One of the most important issues in the process of water supply of the population is the creation of water reserves near settlements for uninterrupted provision of household and drinking needs of the population in the spring and summer period [4]. It is the water reserves in the vicinity of settlements that allow to continuously meet the household and drinking needs of the population. On the territory of Saratov region the arid region is located in the southern and south-eastern parts of the left bank of the Volga River. The most arid areas are part of the Caspian lowland in the south-east of Saratov region. Deep groundwater table excludes the possibility of recharge of small rivers in the summer period, which leads to a significant decrease in their water content, up to complete drying up [7]. In this regard, at the end of the summer period, rivers are fed through a system of artificial irrigation canals from the Saratov reservoir located on the Volga River. Recharge is carried out to replenish the lack of water reserves in water bodies and is associated, as a rule, with considerable financial expenses for water pumping. Similar situations are observed in other southern arid regions of Russia. As a rule, settlements in these areas are supplied with water from reservoirs filled with water from full-flowing rivers, supplied through systems of conduits or canals by pumping.

The presented problem actualizes researches in the field of water supply of population with delivered amount of water and directed to study issues related to monitoring and forecasting changes in water resources reserves in arid regions depending on the influence of climatic factors [2, 3]. One of the specific approaches to addressing this issue entails a method based on the utilization of specialized software, enabling the quantification of water resources through the analysis of computer-processed imagery of water bodies. [5]. In this case, the subject of research are the water resources located in the reservoirs of the arid region, and the object of research is the process of dynamic change of water resources depending on the impact of climatic factors. It is assumed that the area of the water mirror of the reservoir located in the flat area is one of the indicators to determine the volume of its water filling and can be used to indirectly assess the change in water reserves in the reservoir. Therefore, the software, which allows estimating changes of water mirror area of water bodies, will allow revealing regularities of the process of dynamic change of water resources in water bodies and assessing the influence of climatic factors on it. The statistical data processing will facilitate the determination of a statistical correlation for calculating seasonal variations in water resources within the arid region.

2. DATA AND METHODS

The arid region of Saratov region is located in the northern part of the Caspian lowland, in semi-desert and steppe natural zones. The study was conducted on the Solyanka river and six reservoirs of artificial origin located in the southern and southeastern parts of the arid region with the most arid climatic conditions. The investigated lakes and river section are located near the following settlements: Baiguzha (49.989005, 48.447176); Kamyshki (50.257491, 48.371287); Monakhov (50.273165, 48.541149); Novostepnoe (50. 466785, 48.396862); Peschanyi Mar (50.772926, 48.697966); Sysoev (50.088975, 48.355809) which belong to Novouzensk, Alexandrovo-Gaysky and Pitersky municipal districts. The water reserves of the studied water bodies are used to meet the household and drinking needs of the local population.

Assessment of seasonal patterns of changes in water reserves in water bodies in the arid region of Saratov region was carried out according to changes in indicators of water mirror area for the period from 2007 to 2022. The software on calculation of the water mirror area was developed in the ISC of hygiene of FBN "FNTS of medical and preventive technologies of management of health risks" of Rospotrebnadzor in Java programming language version 13.0 and designed to work in the environment of modern computer technologies. Program operation (satellite image analysis and direct calculation of water mirror area) consists of 5 basic stages: satellite image loading; working fragment selection; working fragment tone level adjustment; working fragment binarization; pixels scaling into square meters. To minimize the errors caused by the difference in the average brightness of the processed images, the approach is applied, in which the effect is achieved by automatic adjustment of the tone level of the image fragment. The analysis of image fragments is performed by their binarization (black pixels represent the water surface). Input data for the program are: images of the Earth surface area, taken by means of the Landsat family of satellites and published on the site of the US Geological Survey (https://earthexplorer.usgs.gov). The work does not take into account the difference in spatial resolution of space images. To reduce the calculation error, it is recommended to use images of only one satellite. The data reflecting climatic characteristics (air temperature and amount of precipitation) were obtained from https://www.pogodaiklimat.ru.

Processing of data on the state of water reserves in water bodies of the studied arid region was carried out by indicators of the dynamics of changes in the average values characterizing the total area of water mirrors of water bodies. Statistical dependencies describing the dynamics of water resource variations in an arid region throughout the year are based on the results of correlation-regression analysis conducted to identify and study relationships between quantitative variables by calculating the Pearson correlation coefficient and deriving equations for linear regression. Statistical processing of the results was carried out with the help of Microsoft Excel program and calculators of the website: https://www.medstatistic.ru.

3. RESULTS AND DISCUSSION

In the course of the study, the dynamic indicators of water mirror areas of six artificial lakes located in the most arid region of the Saratov region for the period from 2007 to 2022 were determined (Table 1).

Table 1. Values of the water mirror area of artificial lakes in the arid region of the Saratov region for the period from 2007 to 2022

Settlement locations of artificial lakes	Year	Water mirror area (m^2)				
		March	April	August	September	October
Baiguzha	2007	48875	37501	11746	6147	-
	2009	42395	32007	20834	22074	63798
	2010	295807	59884	27468	38147	34509
	2014	59670	206639	37762	62820	64163
	2018	174687	71582	34604	56872	58328
	2022	58415	-	46611	56445	-
Sysoev	2007	41557	21906	10948	16742	-
	2009	50879	21670	16775	43910	43162
	2010	200744	39218	13955	26326	25054
	2014	55439	26123	4796	61048	10802
	2018	92224	28816	9572	13941	13820
	2022	-	30963	11045	39492	-
Peschanyi Mar	2007	142408	158762	87025	115868	-
	2009	108161	73248	39285	187291	57964
	2010	-	153765	88153	105709	103771
	2014	-	173153	105589	122435	114978
	2018	98768	82417	47087	60591	58289
	2022	-	65058	34341	-	-
Kamyshki	2007	84331	86175	71432	73791	-
	2009	80418	70825	85676	86810	84072
	2010	196835	87401	70626	75239	70760
	2014	102631	70007	36216	16223	17882
	2018	92850	65223	60834	66570	67200
	2022	90490	-	65061	96089	-
Monakhov	2007	52771	432315	34872	67802	-
	2009	72639	31162	29349	48859	43721
	2010	957660	708645	28845	65201	62022
	2014	258211	78171	9352	24411	21297
	2018	670952	243024	4855	11019	9838
	2022	-	177347	10479	18860	-

Novostepnoe	2007	14869	33716	15552	38796	-
	2009	34218	16000	14948	29107	16839
	2010	47410	15670	4249	9381	12710
	2014	51335	15384	9945	26751	23284
	2018	65857	28699	9241	23009	24638
	2022	-	4820	-	-	8314

In order to estimate dynamic changes of water reserves of the Solyanka river the values of water mirror area for the month of observation during spring flood (April) and summer low water (August) were determined. The averaged values of the water mirror area of the section of the studied river Solyanka are presented in Table 2.

Table 2. Average values of the water surface area of the river Solyanka in the arid region of the Saratov region for the period from 2007 to 2022

Year of study	Average water mirror area for the month of the study (M±m), m^2	
	April	August
2007	84300±726	76896±872
2009	65724±812	75639±612
2010	-	-
2014	165411±379	75657±569
2018	160722±484	61845±453
2022	163074±541	69528±246

The area of water mirrors was determined as the total number of pixels (pixel) representing the water surface on the satellite image. Subsequent calibration of the image relative to the terrain scale made it possible to determine the areas of water mirrors of water bodies (Fig. 1).

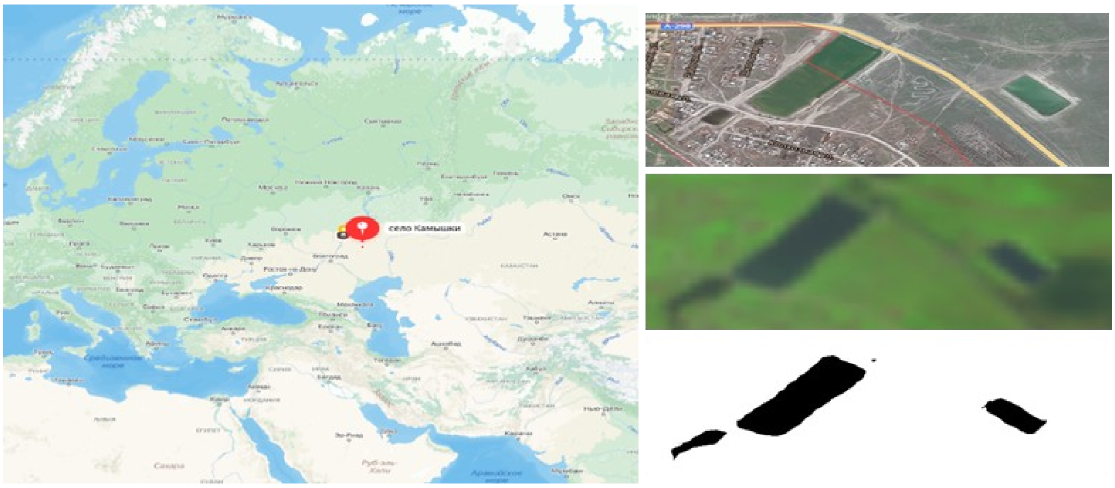

Fig. 1. Place of research and stages of data processing in the calculation of the water mirror area

The areas were analyzed between March and October. The selected period encompasses the following stages of the hydrological cycle: the peak water filling from snowmelt and the maximum depletion of water reserves at the end of the dry period. To perform a statistical analysis, the results of specific indicators for artificial lakes were grouped together for subsequent calculation of average water surface areas (Table 3).

Table 3. Dynamics of changes in average water surface areas of artificial lakes in the arid region of the Saratov region during the period from 2007 to 2022.

Month	Average area values by year (M±m), m^2						Average area value for the study period (M±m), m^2
	2007	2009	2010	2014	2018	2022	
March	124117 ± 70572	64785 ± 12334	339691 ± 159243	105457 ± 43924	199223 ± 104463	-	166655 ± 54161
April	68413 ± 21506	40819 ± 11126	177431 ± 118104	94913 ± 34902	86627 ± 35636	71182 ± 26686	89897 ± 20862
August	38596 ± 14744	34478 ± 11898	38883 ± 14789	33943 ± 16921	27699 ± 10398	33507 ± 10331	34518 ± 1825
September	53191 ± 18205	69675 ± 27618	53334 ± 15791	52282 ± 17676	38667 ± 11314	38266 ± 13349	53430 ± 5186
October	-	51593 ± 22739	51471 ± 33784	42067 ± 18025	38686 ± 11348	-	45954 ± 3808

To assess the influence of precipitation as a climatic factor on the dynamics of changes in the indicator of water surface areas of the studied water bodies, the total precipitation volumes were determined for the periods from November of the previous year to March of the study year and from April to August of the study year. The months of September to October were not considered for calculations due to anthropogenic impact on the irrigation system of the arid region, specifically the pumping of water from the Saratov reservoir to artificially replenish the water levels in the water bodies. It was assumed that the total amount of precipitation during the first period affects the formation of the water surface area of the water bodies due to snowmelt during the spring high water period. The total amount of precipitation during the second period influences the water bodies' ability to replenish water reserves through precipitation during the dry period. During the summer observation period, taking into account the average monthly precipitation and average daily temperatures exceeding +10°C, the Selianinov hydrothermal coefficient of moisture availability (HTC) was calculated. The summarized results of the analysis of climatic factors are presented in Table 4.

Table 4. Characteristics of climatic factors in the study area within the arid region during the period from 2007 to 2022

Year	Total precipitation amount for the period from November to March, mm		Total precipitation amount for the period from April to August, mm		HTC	
	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River
2007	184	166	108	108	0,64	1,00
2009	87	58	173	173	1,00	0,9
2010	194	171	26	26	0,23	0,4
2014	169	119	69	69	0,42	0,5
2018	135	132	22	22	0,13	0,4

2022	268	246	39	39	-	-

The values characterizing climatic factors and the values of dynamic changes in the average water surface area of the water bodies were subjected to correlation and regression analysis. It is known that the dynamics of water reserves in the studied water bodies during the spring period are regulated by the regulation of river flow in the Bolshoy and Malyy Uzen rivers located in the arid region. The high water levels in these rivers during the spring period are provided by the melting waters from the catchment basin and the water injection from the Volga River through the Alexeevskiy irrigation canal. The influence of anthropogenic factors on the water resources of investigated water bodies during the spring freshet is manifested by a diminishment in the strength of the correlation between the dynamics of water resource variations and the cumulative precipitation amount received from November to March, as observed in artificial lakes (R = 0.58) and rivers (R = 0.49). The parameters of the established relationship are presented in Table 5.

Table 5. Characteristics of the correlation relationship between precipitation amount and the average water surface area of water bodies during the spring high water period

Year	Total precipitation amount for the period November to March, mm		Average water mirror area of water bodies in March-April, m^2		R (correlation coefficient)	
	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River
2007	184	166	124117	84300		
2009	87	58	64785	65724		
2010	194	171	339691	-		
2014	169	119	105457	165411	0.58	0.49
2018	135	132	199223	160722		
2022	268	246	-	163074		

To assess the influence of climatic factors during the summer drought period on the dynamics of water storage in the water bodies of the arid region, a correlation-regression analysis was conducted to investigate the impact of precipitation and air temperature, represented by the GTK index, on the changes in the average surface area of the studied water bodies from April to August, reflected in the coefficient (K). As a result, it was found that the dynamics of changes in the water surface areas from April to August are characterized by a significant decrease in water resources due to a predominance of water loss over natural replenishment from seasonal precipitation. The high correlation between the dynamics of water resource changes and the climatic factors during this period is confirmed by the correlation coefficients for artificial lakes (R = 0.85) and the river (R = 0.97). The analysis results are presented in Table 6.

Table 6. Characteristics of the correlation relationship between the GTK index and the coefficient of change in the average surface area of the water bodies during the summer drought period

Year	The coefficient of change in the average surface area of the water body during the period from April to August		The value of the HTC index		R (correlation coefficient)	
	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River
2007	3.2	1.10	0.64	1.00	0.85	0.97
2009	1.9	0.87	1.00	0.9		
2010	8.7	-	0.23	0.4		
2014	3.1	2.19	0.42	0.5		
2018	7.2	2.60	0.13	0.4		
2022	2.1	2.35	-	-		

For an isolated assessment of the impact of precipitation on the indicator of water surface area during the summer drought period (April - August), a correlation-regression analysis of these indicators was conducted. The results of the analysis are presented in Table 7.

Table 7. Characterization of the correlation relationship between the total precipitation volume and the coefficient of change in the average water surface area of water bodies during the summer drought period

Year	The coefficient of change in the average water surface area of water bodies during the period from April to August		The total amount of precipitation during the period from April to August, mm		R (correlation coefficient)	
	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River	Artificial lakes	Solyanka River
2007	3.2	1.10	108	108	0.87	0.86
2009	1.9	0.87	173	173		
201	8.7	-	26	26		

0 2014	3.1	2.19	69	69		
2018	7.2	2.60	22	22		
2022	2.1	2.35	39	39		

The preservation of correlation coefficient (R) and coefficient of determination (R^2) values on previous indicators after excluding air temperature data from the analysis indicates the lack of its significant influence on the change in the surface area of water bodies located in the investigated arid region. According to the conducted analysis, ponds exhibit the most stable indicators.

The Solyanka River is a typical autonomous river of the Saratov region and is not part of the reclamation network that supplies water to the Volga River through the Alexeyevskiy irrigation canal. The graphical representation of the coefficients of change in the average surface area of the water body in Figure 2 clearly demonstrates that the river's water supply lacks stability and directly depends on the degree of aridization in the region. The river experiences high water levels during the spring period due to snowmelt but practically ceases to receive water during the summer period.

"In the driest summer seasons, such as in 2010, the Solyanka River completely dries up, making it impossible to calculate the water surface area. Seasonal fluctuations in water level range up to 49% during the spring flood period and no more than 18% during the summer period, relative to the average value over the observation period."

The analysis of aggregated data within groups over a 3-year observation period reveals significant alterations in the coefficients representing the mean water surface area of the Solyanka River from 2008 to 2022. Specifically, the parameter of water surface area during spring floods shows a dynamic upward trend. Meanwhile, the dynamics of the parameter during summer periods tend to decrease (Figure 2).

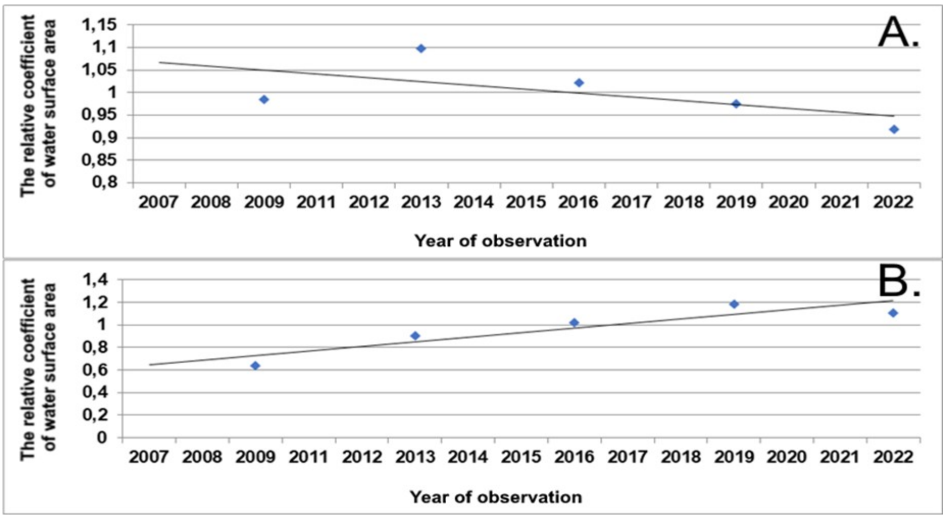

Fig. 2. Dynamics of the average water surface area of the Solyanka River during the period from 2008 to 2022 in different periods: A - summer drought; B - spring flood

Fig. 3 shows the dynamics of natural replenishment of water resources during the summer period in the arid region. The negative trend of the indicator from 2008 to 2022 indicates that the replenishment of water resources in the studied water bodies during the autumn period is possible only through the resources of the Saratov Reservoir.

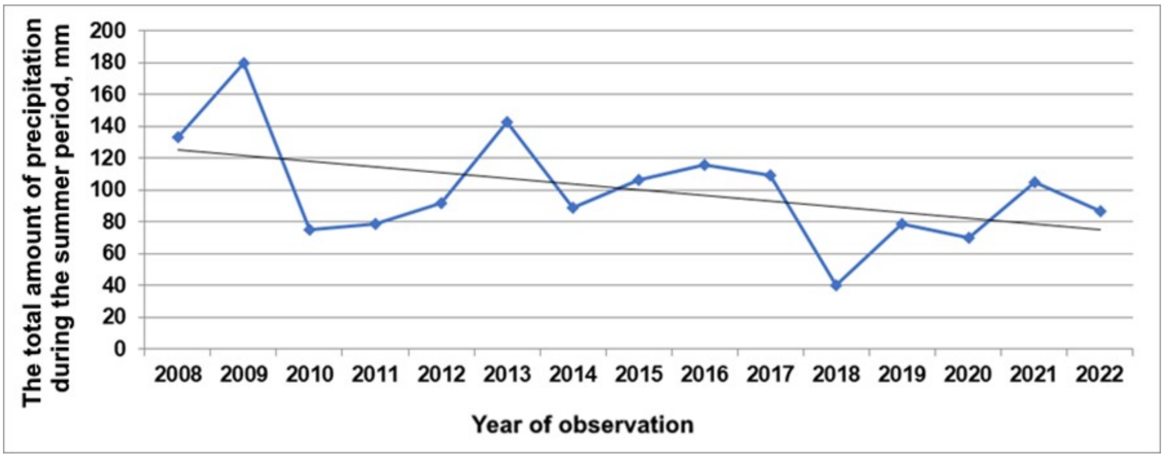

Fig. 3. Dynamics of total precipitation during the summer period in the investigated arid region of the Saratov Oblast

Additionally, according to satellite data, from September to October, there is a process of decreasing water surface area of water bodies by approximately 12±7% of the replenished volume. The presumed cause of this reduction is the absorption of water by the ground in newly inundated territories.

Thus, the analysis of data obtained from satellite imagery has enabled the identification of systematic patterns and long-term dynamics of water reserves in water bodies within the arid region of Saratov Oblast. The results of this analysis establish a statistical relationship describing the fluctuations in the water surface area of water bodies using a parameter derived from the analysis of artificial lakes, which characterizes the volume of seasonal precipitation. The direct correlation between the water volume in the water body and the water surface area makes this parameter crucial for assessing water resources in lowland water bodies. The program's functionality proves most effective in estimating water reserves in water bodies with a channel width exceeding the depth and a shoreline slope not exceeding 45 degrees.

Thus, the influence of the cumulative seasonal autumn-winter precipitation (∑AWP), which contributes to the water volume during the spring flood period, affects the change in the surface area (S) of water bodies. This influence can be described using statistical equation 1:

$$S=-55347{,}65549+1443{,}44769 \cdot \sum AWP \tag{1}$$

The relationship defining the influence of the total amount of seasonal summer precipitation (∑SSP) on the dynamics of the water surface area change in water bodies during the summer drought period (K) is described by equation 2:

$$K=8{,}0655-0{,}04077 \cdot \sum SSP \tag{2}$$

The most significant factor is the correlation between changes in water resources and the total amount of precipitation during the summer period. This regularity allows determining the decrease in water reserves based on known data about the expected precipitation. The analysis of the established relationship demonstrates a direct dependence between changes in water reserves in the reservoir during the summer period and the cumulative amount of precipitation. Meanwhile, the negative dynamics of the amount of precipitation that occurred during the summer periods from 2013 to 2022 indicates increasing signs of aridification in the region.

Thus, the identified regularities indicate an annual trend of further reduction in water resources during the summer periods, necessitating an increase in the volumes of water to be pumped from the Saratov reservoir and higher levels of funding.

4. CONCLUSIONS

The increasing water scarcity problem for both drinking and domestic needs in the arid region of Saratov Oblast necessitates a continuous augmentation of water reserves within water bodies. In this context, the devised program for determining the surface area of water bodies assumes significant importance as it enables the establishment of statistical correlations between the fluctuation of water resources and the climatic factors influencing the amount of seasonal precipitation. The research findings indicate a discernible rise in aridity within the region from 2013 to 2022, which is attributed to a decrease in summer precipitation, leading to an annual depletion of water reserves. Consequently, there has been a corresponding surge in water pumping volumes from the Volga River, particularly in the vicinity of the Saratov reservoir. The implementation of these research outcomes by regulatory bodies responsible for water quality supervision and adherence to sanitation standards will facilitate the remote assessment of water reserves in water bodies across the arid region and determine the availability of water resources for diverse needs, encompassing potable water supply, industrial applications, and agricultural purposes. Notably, the identified patterns prove particularly effective for estimating water volumes in water bodies with channel widths surpassing depth parameters, while also featuring a shoreline inclination not exceeding 45 degrees. The research outcomes significantly enhance the capabilities of specialists engaged in the rational planning and evidence-based decision-making concerning the sustainable exploitation of water resources.

FUNDING

This research was conducted independently, without any financial support or sponsorship from external organizations.

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