Application of advanced computer technologies in determination of irrigation regimes for cotton in water scarcity areas

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Abstract. Agriculture is one of climate change's most sensitive economic sectors. In Uzbekistan, 95% of agricultural products come from irrigated lands. Because the agricultural sector of Uzbekistan meets the population's demand for food and industrial raw materials, ensuring national food security. Different climatic and soil-hydrogeological variations are countrywide significant to assess the possible increase in crop water demand and to determine the water consumption and irrigation regime in the irrigated lands. Therefore, this research aimed to create the hydrological module-zoning (HMZ) map of irrigated lands using geoinformation systems (GIS) technologies by employing spatial soil-hydrogeological data and determining water consumption and irrigation regimes for cotton according to FAO methodology. The area of investigation was the irrigated agricultural lands of the northern regions of the Republic of Karakalpakstan, located in Uzbekistan, which has undergone significant climate change over the last 30 years due to the Aral Sea tragedy and is faced with water scarcity. HMZ map of the study area has been figured out by ArcGIS 10.8 program based on Bespalov's methodology. Determining water demand of cotton developed by developed HMZs based on the CropWat 8.0 program using meteorological parameters. The study showed that identified areas of HMZ and the irrigation regime for cotton by Bespolov in the 80s of the last century have significantly changed because of climate change.

1 Introduction

Global climate change is becoming a factor that can significantly impact all areas of human activity. It negatively impacts the environment in many parts of the planet and the lives and health of the population in various sectors of the economy. The impact of climate change on agriculture, in particular, is high, as agriculture is one of the most weather-dependent sectors of the global economy. Climate change begets 10%-15% more evaporation from water surfaces and 10%-20% more water consumption due to increased plant transpiration and irrigation standards. This leads to an average of 18% increase in non-renewable water consumption. Assessing the risk of a possible increase in water consumption on irrigated

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lands due to climate change, hydrological-modular zoning (hereinafter, HMZ) of irrigated lands, and the development of science-based irrigation procedures for each hydromodule (hereinafter, HM) area to address the efficient use of water resources is a topical issue today [1-3; 5;6].

HMZ consists of the allocation of natural belt-high-altitude zones [2]. The main indicators of HMZ are the soil's mechanical composition and groundwater's surface condition [1]. HMZ is the division of the territory into taxonometric units for the purpose of highly efficient use of land and water resources and the establishment of science-based, differentiated irrigation regimes that ensure consistently high crop yields [5].

The first scientific research on HMZ and the determination of irrigation norm in Central Asia were carried out in 1915 by A.N. Kostyakov [1] and later carried out in 1932-1951 by V.M.Legostaev, S.R. Ryzhova, V.R. Schroeder and others [5;6]. HMZ of irrigated lands of Uzbekistan and the irrigation procedures for major agricultural crops were developed in 1986 by Bespalov et al. (former Sredazgiprovodkhlopok), and this information is still used to determine crop water consumption and water use plans [1].

According to N.F. Bespalov's methodology, zoning, considers the different use of groundwater by plants depending on the depth of their occurrence and the intensity of moistening of the root-inhabited soil layer, which determines their share in the formation of the crop. Depending on the thickness of the mechanical composition, structure, and composition of the soil and ground in the aeration zone and groundwater depth, a scale of nine hydromodule zones was recommended.

The water use system in Uzbekistan has changed radically since 1991. Every year, water consumption from rivers had been stopped in September, and canals and collector-drainage systems were inspected and constructed before salinization began. Due to the use of the cotton-winter wheat rotation system, irrigation networks are working continuously throughout the year. Moreover, the load on the collector-drainage system has greatly increased. These, in turn, affect the process of soil formation, and there is an increase in the area of hydromorphic soils [7-10].

There is a serious shortage of irrigation water in the country and for agriculture. Due to the growing demand for water in agricultural crops due to climate change, the efficient use of water in agriculture is a priority. Periodic data on the analysis of precipitation in the northern region of the Republic of Karakalpakstan show that the annual rainfall is 60-70 mm. Uneven distribution, low rainfall, low water holding capacity of soils are the main causes of crop stress [17].

Therefore, it is important to change the HMZ of irrigated lands developed in the 1980s, the distribution of irrigated lands by HM regions, and the definition of science-based irrigation procedures for agricultural crops in each HM region [24-25].

Today, the determination of crop water demands requires up-to-the-date and innovative technologies for the development of highly precise digital HMZ maps implementing geographic information system (ArcGIS) technologies [8, 13-14] and other computer technologies using based on meteorological parameters, i.e., CropWat 8.0 [29].

GIS is an automated system with many graphical and thematic databases. The system combines model and computational functions capable of performing database-based work, converting spatial data into a cartographic form, monitoring, and making decisions. The use of GIS technologies in the management and water resources ensures that most of the tasks are performed easily, quickly, and accurately [14-19, 26, 27, 28].

2 Materials and Methods

2.1 Study area

These studies were conducted on irrigated agricultural lands of the northern part of the Republic of Karakalpakstan in the Aral Sea Basin, specifically in Bozatau, Kegeyli, Muynak, Takhtakor, Khojayli, Chimbay, Shumanay, Kanlikul, Karaozak, Nukus, and Kungrad districts (Figure 1) [1-2].

According to the statistics, the irrigated area in the northern regions of the Republic of Karakalpakstan, as in most regions of Uzbekistan, has been declining over the years from 2000 to 2021. The main reason for this is the intensification of climate change, water scarcity, degradation, the allocation of land for state and public needs, and the creation of new gardens (intensive) and vineyards based on government decisions and programs. Today, the total land area in the balance of the Republic of Karakalpakstan is almost 16.7 million hectares, of which 418,517 (2.51%) hectares of irrigated land, of which 270,875 (1.62%) hectares are located in the northern part [15-21].

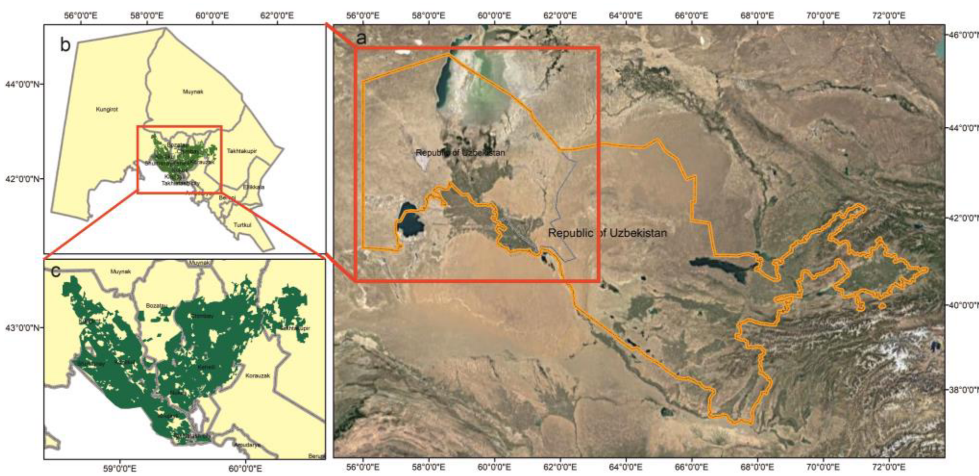

Fig. 1. Map of the study area**:** a) Location of the Republic of Uzbekistan; b) Location of the northern regions of the Republic of Karakalpakstan; c) Location of irrigated lands in the northern districts of the Republic of Karakalpakstan

2.2 Methodology

HMZ of irrigated lands of the northern districts of the Republic of Karakalpakstan was created based on the methodology developed by Bespalov (Table 1) [1; 3-6]. Since the mechanical composition of soils is one of the key factors in determining the hydromodular zoning and irrigation norms, data on the mechanical composition of soils were digitized using a paper-based soil map developed by scientists at the Institute of Soil Science of the Republic of Uzbekistan using the ArcGIS program. Then, the mechanical composition of soils on irrigated lands in the northern part of the Republic of Karakalpakstan was classified based on classes of light, medium, and heavy mechanical composition (Figure 2). Climatic data were collected from existing meteorological stations in the study area.

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Table 1. Bespalov HMZ classes

Hydromodule zone number	Soil condition	Groundwater level, m
Automorphic soils		
I	Low-layer sand and thick-layer sand, located on sand-gravel	> 3.0
II	Medium-layered sand and thick sand, and light sand on top of sand-gravel	> 3.0
III	Thick medium, and heavy sand and muddy	> 3.0
Semi-automorphic soils		
IV	Sand, medium and low thickness layered sand and clay,	2.0 - 3.0
V	Light and medium sand, single-layer heavy sand, lightening down,	2.0 - 3.0
VI	Heavy sandy, muddy, layered with the same layer and different mechanical composition, layered,	2.0 - 3.0
Hydromorphic soils		
VII	Sandy and loamy, low and medium thickness layered sand and clay	1.0 - 2.0
VIII	Light and medium sand, single-layer, heavy sand that loosens down	1.0 - 2.0
IX	Heavy sand and clay, layered with the same layer, different mechanical composition	1.0 - 2.0

Hydromodule zoning is one of the main steps in determining the surface distribution of groundwater. Data from observation wells are used to determine the surface distribution of groundwater in the area.

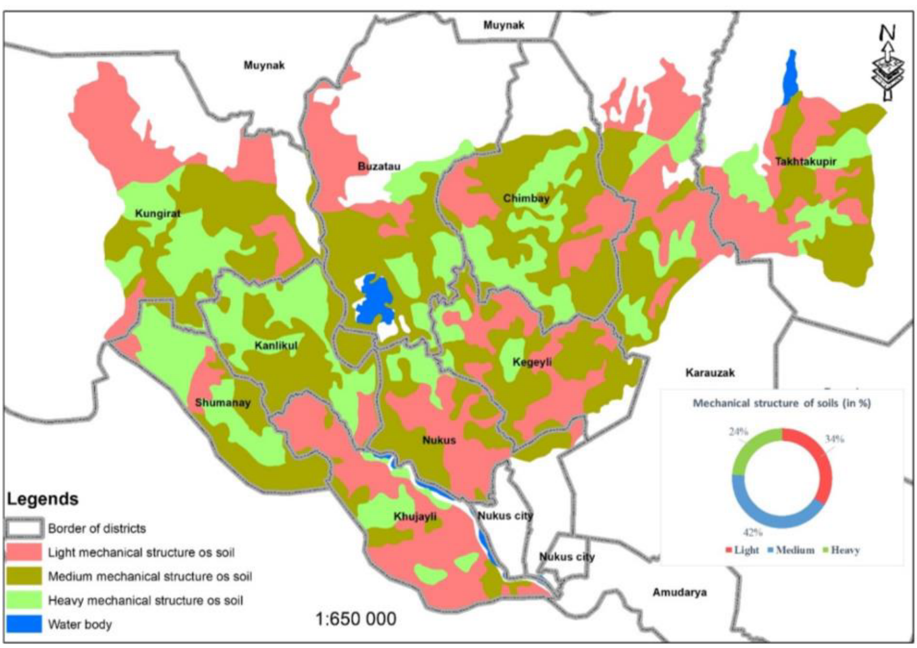

Fig. 2. Geovisualization of soils in the geological database according to the mechanical structure of soil

The coordinates of the geographical location of the observation wells in the study area were carried out on a GNSS wave receiver of the HI-Target i70, and their database was created based on the ArcGIS program. The five-year average value of the data collected on the surface change of constant groundwater in the electronic geotagmatic database of observation wells was included in the attribute data of observation wells (Figure 3).

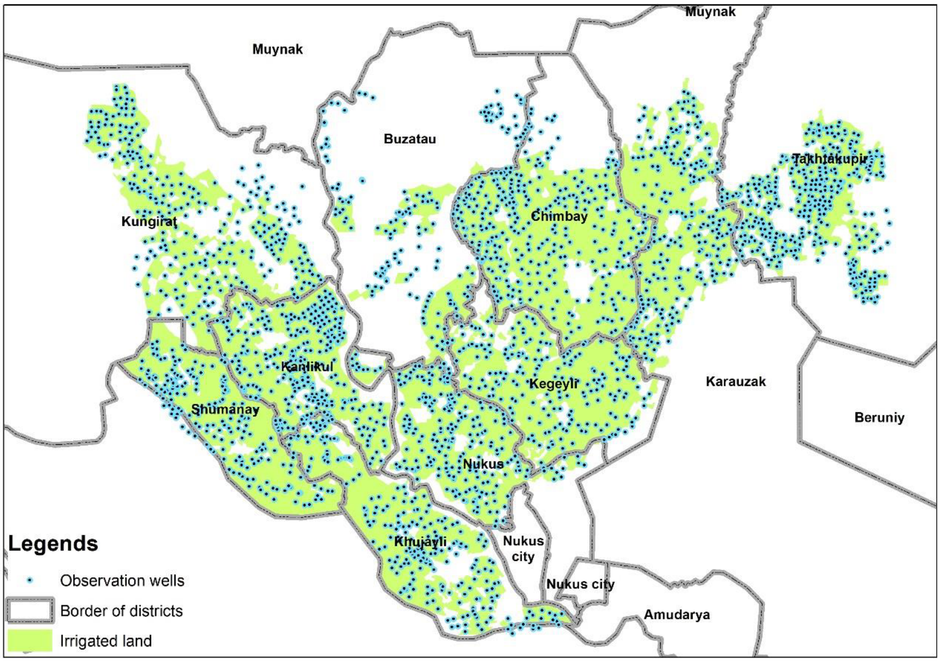

Fig. 3. Distribution of observation wells in study area

There are currently 2,438 monitoring wells in the irrigated areas of the northern part of the Republic of Karakalpakstan for continuous monitoring of groundwater levels and their mineralization (Table 2).

Table 2. Republic of Karakalpakstan is located on irrigated lands, observation wells

No.	Districts	Observation wells	Attached area, '000 ha
1	Bozatau	158	14,539
2	Korauzak	249	32,060
3	Kegeyli	187	24,843
4	Kanglikol	275	32,527
5	Kongirat	273	38,289
6	Nukus	217	32,391
7	Takhtakupr	349	19,591
8	Khojayli	238	40,831
9	Chimbay	310	26,497
10	Shumanay	182	6,707
Overall		**2,438**	**268,276**

To further increase the accuracy of zoning, the exact amount of irrigated land in the study area was determined; a database of irrigated land and an electronic digital map was created. Other land data (settlements, irrigation and water facilities, and non-agricultural land) were compiled on a clear scale (Figure 4).

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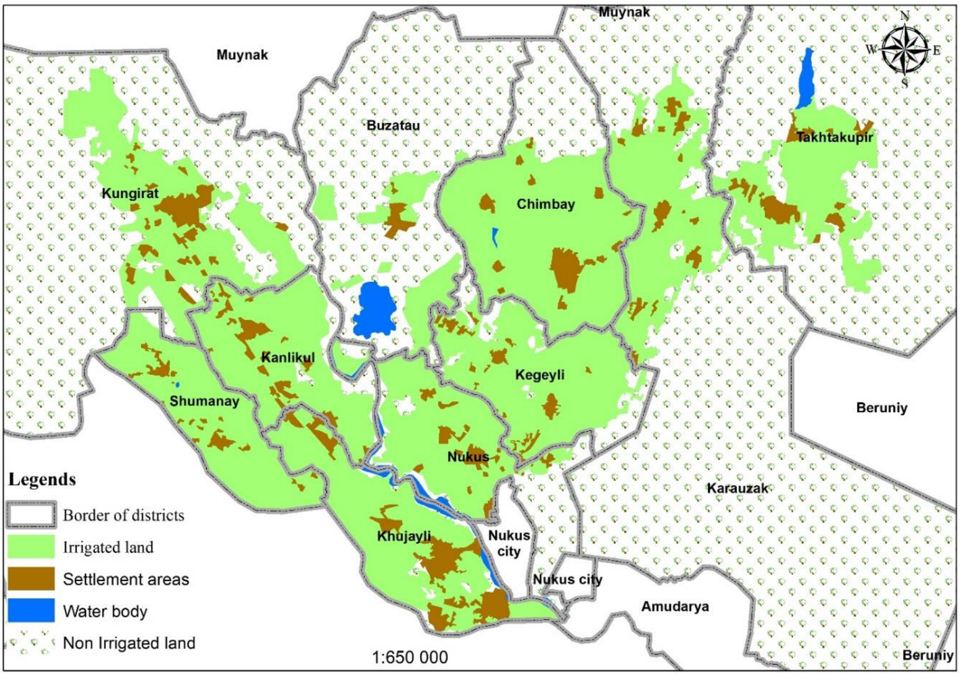

Fig. 4. Geovisualization of settlements, waterworks, and non-agricultural lands in the geospatial database

2.3 Data analysis

In the development of HMZ maps of irrigated lands using the Inverse Distance Weighting (hereinafter, IDW) interpolation method and raster calculator panel of ArcGIS program were used. The IDW interpolation algorithm was used to analyze and visualize the surface distribution of groundwater [19; 23].

The advantage of the IDW algorithm over other algorithms is the ability to increase the accuracy levels by changing the individual power indicator settings. The interpolation results are evaluated based on the values of the points and the distance between them. IDW mainly uses power parameters to control the effect of certain points on interpolation points. The power rating is a positive number; the larger the power rating and the greater the effect of distance on the result, which varies due to a special calculation. Points closer to certain values are more affected than points farther away [9, 26, 28].

In this study, a map of the geographical distribution of groundwater level was developed based on the data obtained on the groundwater level in the case when the power parameters of the IDW algorithm were set to two (Figure 5).

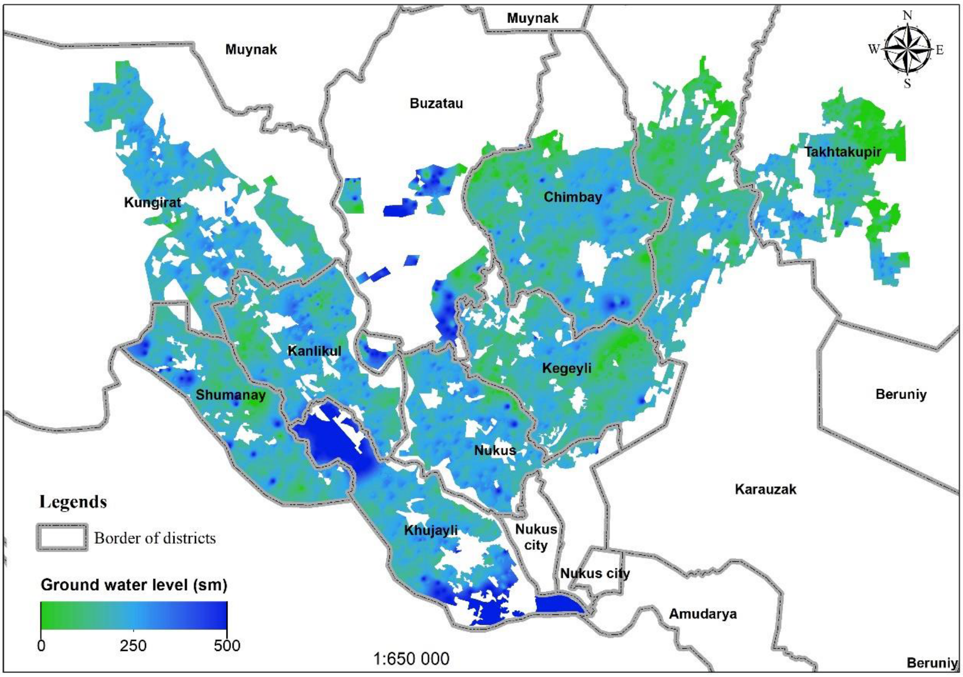

Fig. 5. Distribution of groundwater level, cm.

HMZ algorithm has been developed for raster calculation, based on the obtained thematic layers of soil and groundwater level, to determine the exact areas of HMZ in irrigated lands of the northern part of the Republic of Karakalpakstan (Table 3).

Table 3. Algorithm developed for HMZ maps by ArcGIS

Hydromodular regions	Groundwater level, (cm)	Algorithm
I	300 <	Con ((("mss" == 1) & ("gwl"> 300)), 1,0)
II	300 <	Con ((("mss" == 2) & ("gwl"> 300)), 1,0)
III	300 <	Con ((("mss" == 3) & ("gwl"> 300.01)), 1,0)
IV	200-300	Con ((("mss" == 1) & ("gwl" <= 300) & ("gwlv"> 200)), 1,0)
V	200-300	Con ((("mss" == 2) & ("gwl" <= 300) & ("gwl"> = 200)), 1,0)
VI	200-300	Con ((("mss" == 3) & ("gwl" <= 300) & ("gwlv"> = 200)), 1,0)
VII	100-200	Con ((("mss" == 1) & ("gwl" <= 200) & ("gwl"> = 100)), 1,0)
VIII	100-200	Con ((("mss" == 2) & ("gwl" <= 200) & ("gwl"> = 100)), 1,0)
IX	100-200	Con ((("mss" == 3) & ("gwl" <= 200) & ("gwl"> = 100)), 1,0)

Note: mss is mechanical structure of soil, where 1, 2, and 3 are light, medium, and heavy degrees of mechanical structures of soil, respectively; gwl is groundwater level in centimeters.

Crop demand for water was determined based on the CropWat 8.0 program developed by the FAO. Separately, the evapotranspiration of agroecological units (ET0) was determined by the Penman Monteth method [29]. The methods of systematic analysis and mathematical statistics, as well as the "Methods of conducting field experiments" of the Scientific Research Institute of Cotton Breeding, Seed Production and Agricultural Agrotechnology (Tashkent, Uzbekistan), were used in the research [10].

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3 Results and Discussion

Irrigated lands of the northern districts of the Republic of Karakalpakstan were divided into nine HM zones based on the mechanical structure of the soil, location, and groundwater level (Figure 6 and Table 4) using GIS technologies.

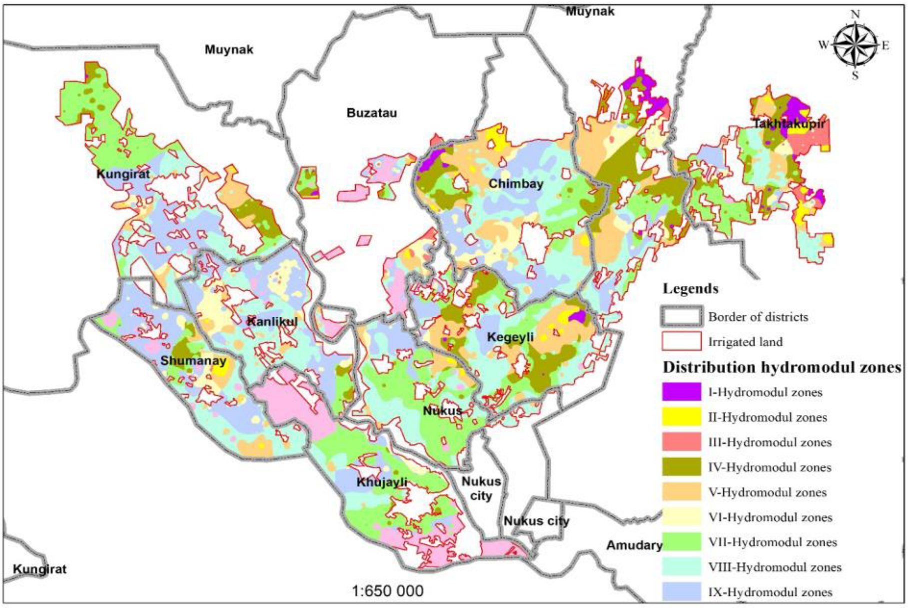

Fig. 6. HMZ map of northern districts of the Republic of Karakalpakstan, Uzbekistan

The following results can find out from the research on the development of scientifically HMZ maps of the northern part of the Republic of Karakalpakstan: Hydromodel zones I, II, and III, which belong to the automorphic soils and have a groundwater level deeper than 3.0 meters, cover 13,520 hectares or 5.03% of the total irrigated area; Semi-automorphic soils (IV, V and VI HM areas) with a groundwater level of 2.0-3.0 meters cover 73,804 hectares or 27.52% of the total irrigated area. The remaining 180,952 hectares, or 67.45% of irrigated lands, fall into the VII, VIII, and IX HMZ with a groundwater level of 1.0-2.0 meters (hydromorphic soils) (Figure 7).

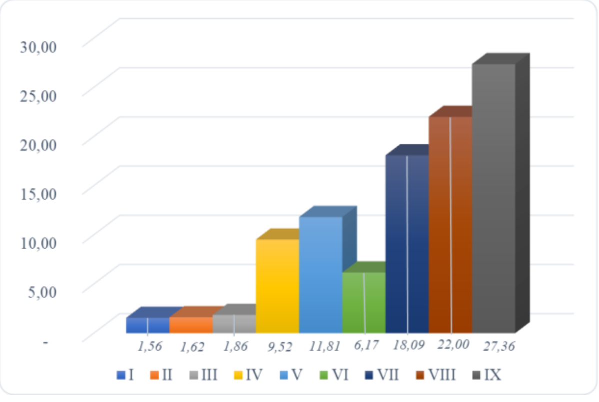

Fig. 7. Distribution of HMZ in the northern regions of the Republic of Karakalpagistan

In the northern part of the Republic of Karakalpakstan in 2020, the amount of evapotranspiration (mm/day), precipitation and useful precipitation (mm), max and min air temperature (°C), relative humidity (%), wind speed (m/s), sunlight shading duration (hours), radiation (mdj/ml/day) data, the dynamics of change over the months was determined (Figure 8).

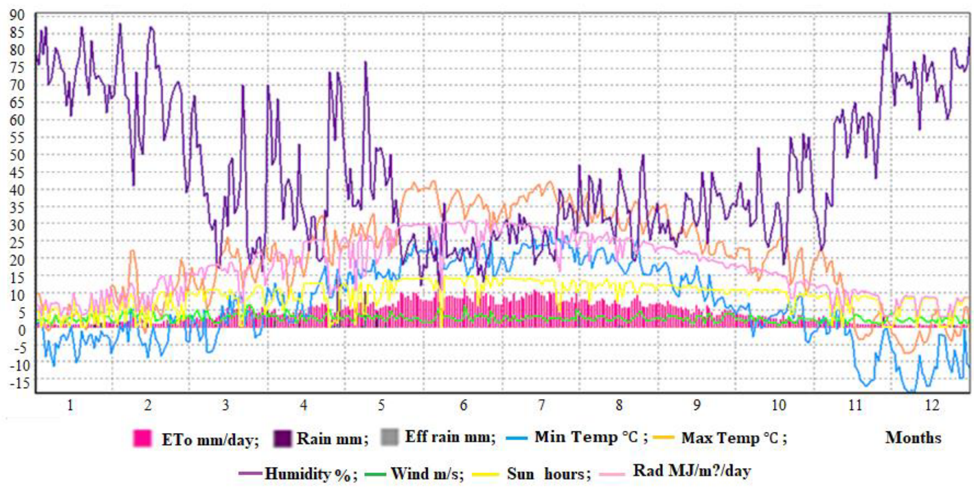

Fig. 8. Dynamics of climatic parameters in the northern part of the Republic of Karakalpakstan.

Using FAO's CropWat program, seasonal irrigation standards for cotton were determined for the northern region of the Republic of Karakalpakstan. In this case, the crop coefficients were adopted according to the data of the Research Institute of Irrigation and Water Problems [18]. In the northern part Republic of Karakalpakstan, the norms of seasonal irrigation of cotton were 4200-7000 m3/ha in the hydromodule regions (Figure 9).

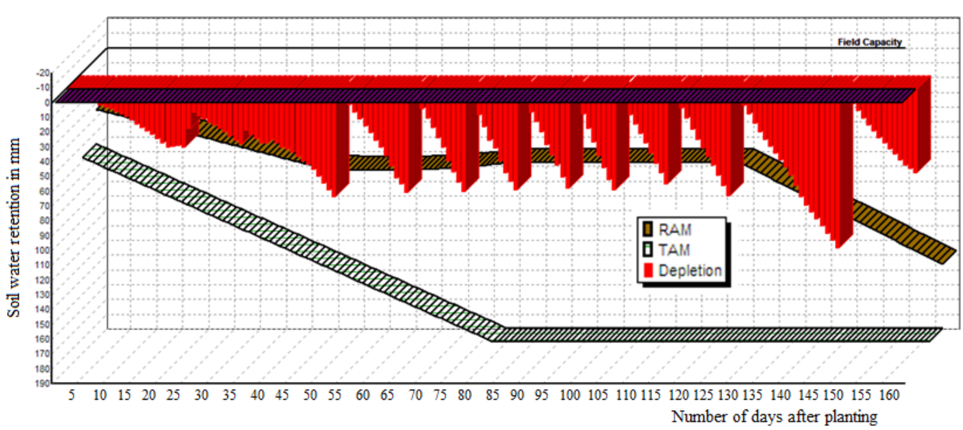

Fig. 9. Irrigation norm for cotton according to the FAO method in the northern part of the Republic of Karakalpakstan.

As mentioned above, the last hydromodul zoning of irrigated land in Uzbekistan was carried out in 1986. During 35 years, significant changes occurred due to irrigation systems and climate change. The tendency of hydromodule zones and irrigation norms are revealed in Table 4 below.

Table 4. Changes in HMZ and irrigation norms for cotton in the northern regions of the Republic of Karakalpakstan between 1985 and 2020

HMZ	Areas of HMZ in 1985 (%)	Areas of HMZ in 2020 (%)	Difference (%)	Irrigation norm for cotton in 1985 by Bespalov (m3/ha)	Irrigation norm for cotton in 2020 by CropWat 8.0 (m3/ha)	Difference (m3/ha)
I	-	1.56	+1.56		6400	6400
II	15.2	1.62	-13.58	6100	6000	-100
III	3.7	1.86	-1.84	5800	5200	-600
IV	2.8	9.52	6.72	6400	5900	-500
V	32.9	11.81	-21.09	4400	4900	500
VI	20.5	6.17	-14.33	5300	4500	-800
VII	1.5	18.09	16.59	5000	5000	0
VIII	14.9	22.00	7.1	2900	3550	650
IX	8.5	27.36	18.86	3800	3400	-400

It is seen from table 4 that, during 35 years, HMZ and seasonal irrigation norms for cotton in hydromodular zones in the northern part of the Republic of Karakalpakstan changed to 6400 (+6400) m3/ha in I hydromodule zone (+1.56%), 6000 (-100) m3/ha in II hydromodule zone (-13.58%), 5200 (-600) m3/ha in III hydromodule zone (-1.84%), 5900 (-500) m3/ha in IV hydromodule zone (+6.72%), 5900 (-500) m3/ha in IV hydromodule zone (+6.72%), 4900 (+500) m3/ha in V hydromodule zone (-21.09%), 4500 (-800) m3/ha in VI hydromodule zone (-14.33%), 5000 m3/ha in VII hydromodule zone (+16.59%), 3550 (+600) m3/ha in VIII hydromodule zone (+7.1%) and 3400 (-400) m3/ha in IX hydromodule zone (+7.1%). HMZ – I had been formed with small percentages (1.56 %). Moreover, with HMZ – II, IV, V, VI, VII, and IX, significant changes have been accrued. It means groundwater levels and soil structure have changed over the years in these areas. However, for these areas still, former irrigation norms are being used.

4 Conclusions

Hydromodular zoning of irrigated lands - the purpose of dividing the area into taxonomic units is the efficient use of land and water resources and the use of science-based irrigation regimes and high crop yields. Hydromodule zoning is a part of the soil-ameliorative zone, soil thickness, mechanical composition, location in the aeration zone, water-physical properties, location of groundwater level, irrigation regime, norms, and hydromodule ordinate. It is generally characterized by the yield of agricultural crops. Therefore, the hydromodule zoning of irrigated lands and the creation of its electronic maps will allow making quick decisions on the efficient use of water resources and their rational management. Using geoinformation systems technology (GIS) in agriculture and water management solves many problems quickly. Using CropWat 8.0 software, reference evapotranspiration and radiation rates were determined across the research objects. These indicators are 17.6 mdj/ml / day and 3.22 mm/day in the Khorezm region, 17.3 mdj/ml / day, and 4.22 mm/day in the northern part of the Republic of Karakalpakstan. According to the CropWat 8.0 program, it is advisable to conduct lysimetric studies to further increase the accuracy of cotton in the development of science-based irrigation regimes in different soil-hydrogeological conditions on pilot plots to determine plant coefficients.

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