PAPER • **OPEN ACCESS**

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To cite this article: D M Onopriienko *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1254** 012087

Assessment of the hydrogeological and ameliorative state of the Kilchen irrigation system territory

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Abstract. Climatic changes, physical and moral deterioration of the main funds of land reclamation systems in Ukraine prompt a change in conceptual approaches and reform of the water management system for efficient use of irrigated lands. One of the components of the agricultural hydrotechnical reclamation development is the provision of an appropriate level of ecological and reclamation status of irrigated lands and territories adjacent to irrigation systems (first of all, an open network of canals). The purpose of these studies is to assess the modern technical and hydrogeological-ameliorative state of the Kilchen irrigation system (total area of 35.3 thousand hectares) for a long period of operation of more than 50 years. The main research methods were field diagnostic surveys of the technical conditions of the main structures and elements of the irrigation system (open channels in the earthen channel). The trends of changes in climatic conditions of the territory over the last decade are analyzed. Analytical processing of the stock materials data and field observations of changes in the groundwater level, its chemical composition and mineralization in 24 observation wells along the main channel was carried out. The main chemical composition of groundwater in the research area is characterized as sulfate and sodium-calcium with total mineralization in individual areas from 0.6-0.9 to 1.7-3.5 g/l. According to the known methods of R.O. Bayer and V.A. Kovda calculations of the predicted change in the level and critical depth of groundwater have been performed. The established terms of change vary between 9-11 years, provided that irrigation is intensified and the irrigation system is fully operational. Based on the forecasting results, groundwater mineralization is expected to decrease from 3.5 g/l to 2.27 g/l between 2021 and 2029. It was determined that the level of groundwater above the calculated critical levels in different years occupies from 30.7 to 51.0% of the territory in the area of operation of the Kilchen irrigation system. The reclamation state of part of the irrigated lands in 2021 with a total area of more than 13.000 ha was distributed according to the following criteria: 12.000 ha – favorable, 1.200 ha – satisfactory, about 50 ha – unsatisfactory due to the manifestation of soil salinization processes. As of 2021, of the soils on an area of about 10.000 hectares that were studied, almost 8.500 hectares of soils are non-saline, more than 1.200 hectares are slightly saline, and about 50 hectares are moderately saline. For comparison, in 2003, all soils on the same area were non-saline, which indicates the deterioration of the ecological and melioratic state of the territory and the decrease in the quality of irrigation water.

1. Relevance

One of the most important issues of Ukraine's national security during the war is ensuring food security [1]. Nowadays, the agrarian sector of the economy has the most dynamic development and provides a significant share of currency inflows to Ukraine. With rapid changes in climatic conditions and a shortage of soil moisture, obtaining consistently high yields of agricultural crops, regardless of weather conditions, is ensured by irrigation. Almost all irrigation systems in Ukraine were built in the 60s and 70s of the last century. The terms of their technical operation have exceeded (or are approaching) the project indicators. Among the main factors that negatively affect the operation of hydromelioration systems, the following are distinguished: inadequate state funding, which does not provide the opportunity to carry out current and capital repairs in a high-quality and timely manner; physical wear and tear of fixed assets; significant non-productive losses of water from the irrigation network, causing flooding or inundation of adjacent territories, soil salinization, etc.; the high cost of irrigation water and the use of low-quality water resources [2].

The consequence of long-term operation of hydromelioration systems at an unsatisfactory and insufficient level of technical operation is the deterioration of the ecological and meliorational state of the territories adjacent to these systems. This problem requires the development of appropriate technical and technological solutions for the further development of irrigation reclamation in Ukraine [3]. It should be noted that the priority areas of development indicated in the "Strategy of Irrigation and Drainage in Ukraine for the period until 2030" approved by the order of the Cabinet of Ministers of Ukraine No.688 dated August 14, 2019 are:

- conducting a detailed audit of the use of reclaimed land and inventory of land reclamation systems;
- implementation of institutional reforms of shade resource management and land reclamation;
- creation of the umbrella organization for effective management and reliable operation of reclamation systems;
- implementation of investment and infrastructure projects for the restoration and development of land reclamation in Ukraine.

At the same time, in order to realize the set goals, it is necessary to carry out a thorough assessment of the current state of both the technical resources of the country's reclamation complex as a whole, and the ecological and reclamation state of the territories adjacent to the irrigated systems in particular [4]. In domestic and international practice, the importance of systematic long-term data collection on the level of groundwater on irrigated lands is noted [5]. Such data are critical to research and solve many of the complex environmental problems of adjacent irrigated areas that irrigated agriculture commonly faces. Foreign researchers pay great attention to the periodicity of observing the ecological and meliorational state of irrigated lands [6] and establishing the impact of irrigation systems on the state of the surrounding natural environment [7].

At responsible facilities, hydrographs are most often used, which record data continuously, since periodic monitoring may not reflect short-term loads in the form of extreme fluctuations in water levels in hydraulic reactions. The disadvantage of constant monitoring is the need for large capital investments. However, it does not always provide an opportunity to see a global change in the trend of the groundwater level. Most often, observations are analyzed every 5-10 years.

Recently, the ecological and reclamation state of irrigated lands is affected not only by their technical condition, but also by changes in climatic indicators. The global trend of increasing air temperature during the growing season and decreasing the amount of productive precipitation leads to a greater manifestation of the salinization and salting processes of irrigated soils [8]. Climate change leads to a decrease in productive moisture in the soil and a decrease in the level of groundwater due to the lack of seasonal replenishment. Due to the lack of productive precipitation, some European countries, in particular France, state an active reduction of the aquifer and a decrease in the level of groundwater. According to the regulations in Ukraine, irrigation systems monitor the condition of irrigated and adjacent lands according to hydrogeological indicators; monitor indicators of the soils and groundwater chemical composition, the technical condition of the reclamation system, flooding of nearby settlements within the area of the reclamation system operation etc. [9].

Such monitoring of reclaimed land is carried out with the aim of ensuring rational use of land and water resources, identifying the causes of their unsatisfactory state, quality and pollution, timely implementation of reclamation measures to prevent soil degradation and harmful effects of water, reproduction of soil fertility, protection of water and land from pollution, timely performance of repair and restoration works (reconstruction) [10].

State programs are relevant and necessary to ensure the collection of data for ecological and remedial monitoring and the future forecast of the negative consequences of the impact on the environment. These programs make it possible to efficiently use the network of observation wells and monitor the water level in them at the local, regional, and state levels. Monitoring the level of groundwater on irrigated areas is an important task in the organization and implementation of ecological and remedial monitoring. Thus, the purpose of this work is to assess the hydrogeological and reclamation state of the territory in the zone of the Kilchen irrigation system influence at the current stage of exploitation.

2. Research methods

Field diagnostic surveys of the technical condition of the irrigation system's main structures and elements (open channels in the earthen channel) were carried out. Analytical processing of data from stock materials and field observations of changes in the level of groundwater and its quality in observation wells was performed. The calculation of the forecast change in the level of the groundwater critical depth was carried out using various methods (according to the methods of R. O. Bayer and V. A. Kovda). QGIS, AutoCAD, and Microsoft Excel software packages were used during the processing of the material.

3. Results and discussion

The Kilchen (formerly Frunzen) irrigation system is located on the territory of the Dnipropetrovsk region. The irrigation system was built in two phases: the first was put into operation in 1970, and the second in 1975. The total area of the irrigation area is 35.3 thousand hectares (20.1 thousand hectares and 15.2 thousand hectares, respectively). The source of power for the Kilchen irrigation system is the Dnipro Reservoir on the Samara River, from which water flows through a 4.25 km long canal by gravity to the main pumping station No. 1 (MPS-1) and is fed into the main canal of the first line (26.8 km long). The channel of the underwater channel is earthen, and the channel itself is designed for the passage of water up to 20 m^3/s.

Main and distribution canals (total length 47 km) of the Kilchen irrigation system are built with an anti-filtration coating mainly from reinforced concrete slabs laid on polyethylene film, as well as in open reinforced concrete trays (5.2 km long).

The drainage network was built on an area of 24.6 thousand hectares, which makes it possible to maintain an optimal water-salt regime in the irrigated and adjacent territories. A cut-off horizontal drainage (3.6 km long) was created along the main canal of the first stage, and forest strips were planted along the borders of the fields. The first stage of the Kilchen irrigation array is located on the left bank of the Dnipro River within the Dnipro and Tsarychan districts of the Dnipropetrovsk region (figure 1).

The irrigation array is located mainly on the second floodplain terrace of the Dnipro and partially on the watershed plateau of the Kilchen and Chaplinka rivers. The surface is flat, dissected by a truss-beam network. Soils are not saline. The soil cover consists mainly of ordinary low- and medium-humus rich chernozems. Hydrogeological conditions are marked by the presence of an aquifer in anthropogenic sediments at a depth of 2-15 m, on the watershed

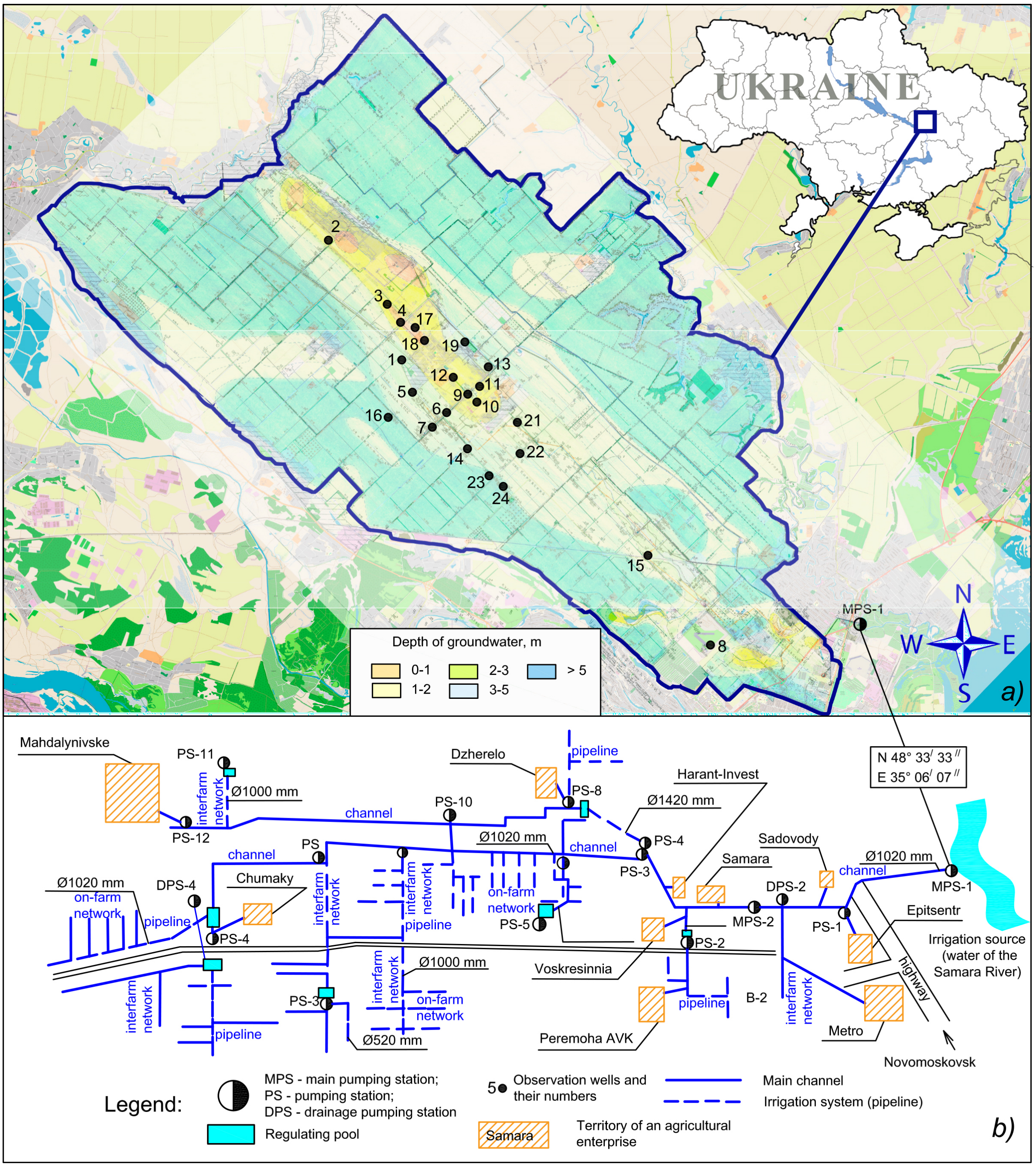

Figure 1. Overview diagram of the Kilchen irrigation system: a) – an area within the region with specific levels of groundwater; b) – a diagram indicating the positions of channels and pumping stations.

plateau – up to 45 m. The chemical composition of groundwater is sulfate and sodium-calcium with mineralization from 0.6-0.9 to 1.7-3.5 g/l.

The northern border of the irrigation system runs along the main channel and along the village of Ulyanivka to the Chaplinka River, and the western part of the massif is limited to the village of Petrikyvka. The southern border runs along the Dnipro-Poltava highway, and the eastern border along the Dnipro-Novomoskovsk highway. The total length of the irrigated massif is 35 km with a width of 7-9 km.

(a)

(b)

Figure 2. Anti-filtration lining of the main channel with reinforced concrete slabs: (*a*) – at the construction stage in 1965 (archival photo); (*b*) – unsatisfactory technical condition and damage at the current level of operation (author's photo).

The natural boundaries of the irrigation array are: in the north – the slopes of the watershed plateau, in the south – the ledge of the first floodplain terrace of the Dnipro River, in the east – the Kilchen River and in the west – the Chaplinka River. Next to the irrigation network, there are 53 agricultural enterprises with a total area of about 13.331 hectares, including 1.790 hectares of irrigated land. Agricultural enterprises specialize in the production of grain and vegetable and meat and dairy products.

As of April 1, 2021, the irrigated area under the control of the Kilchen irrigation system in the Dnipro district is 96,601 hectares, including 1,549 hectares of actually irrigated land.

According to the results, own field diagnostic surveys of the main channel testify to its unsatisfactory technical condition at the current level of operation (figure 2). In particular, the damage to the anti-filtration coating of the canal, the development of shrubby vegetation, and the destruction of individual water supply and water permeable elements of the structure are noted.

The effectiveness of irrigation hydrotechnical reclamations and the quality of surface and groundwater are impacted by rapid changes in climate. The climatic conditions in 2010 and 2018 showed an increase in air temperature by 1.97 °C and 0.84 °C compared to the long-term average temperature of 9.2 °C (table 1). However, in 2021, the average annual air temperature was almost similar to the long-term values. In 2010, the amount of precipitation was 13.3 mm higher than the long-term average value of 429 mm, while in 2018 and 2021, the precipitation levels exceeded the long-term average by 255.7 mm and 252 mm, respectively. Data on meteorological observations from previous years were obtained from open sources on the internet and archives of the Dnipropetrovsk Hydrogeological and Reclamation Expedition.

The assessment of the hydrogeological and reclamation state of irrigated lands was carried out based on the analysis of the groundwater level depth during the vegetation and irrigation period of the corresponding year. On the area of the irrigation array, the regime network consists of 255 observation wells.

In 2021, the distribution of controlled areas according to the depth of groundwater levels of 2-3 m on the irrigation array was 302 hectares, with a level of 3-5 m – more than 4 thousand hectares, and with a level of more than 5 m – about 9 thousand hectares. The level of groundwater in some observation wells by years of research is shown in figure 3.

Table 1. Dynamics of changes in climatic indicators at the object of research.

Month	Average air temperature, °C			Precipitation, mm		
	Year			Year		
	2010	2018	2021	2010	2018	2021
January	-1.00	-2.9	-2.0	0.2	72.6	57.9
February	0.20	-2.6	-3.8	0.2	46.2	53.5
March	2.00	-1.5	1.6	17.5	144.9	49
April	10.5	12.9	8.0	19.9	16.9	54.4
May	17.4	18.9	15.8	67.6	31.5	27.9
June	22.7	21.7	19.5	48.9	53.0	202.5
July	24.8	22.5	23.6	70.3	79.3	70.8
August	25.8	23.4	22.8	11.2	0.0	51.1
September	16.9	17.8	13.8	55.8	74.4	23.9
October	6.4	11.5	8.4	53.4	22.8	2.2
November	8.8	0.6	4.3	38.1	37.4	38.2
December	-0.5	-1.8	-0.9	59.2	105.7	49.6

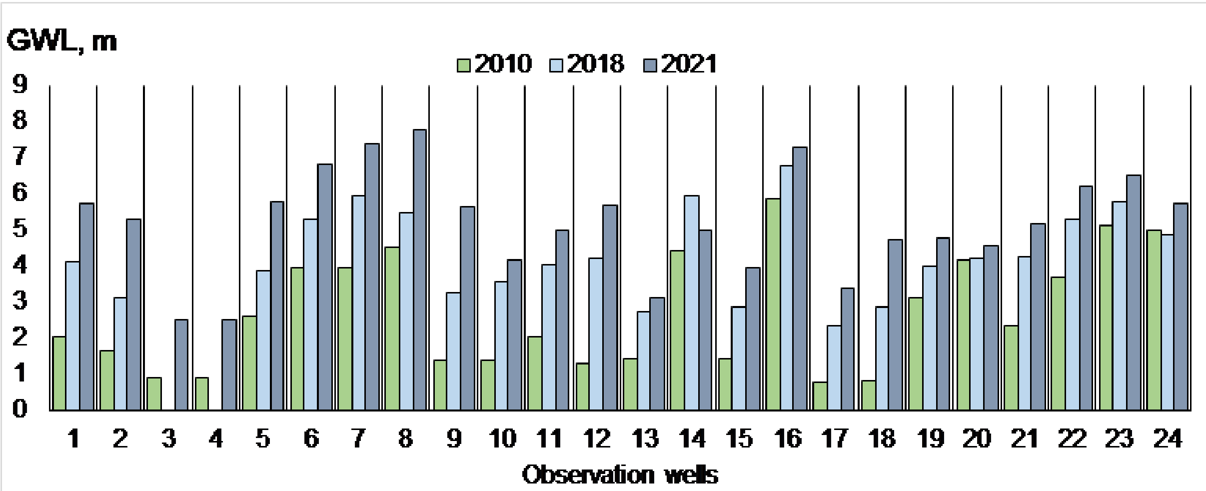

Figure 3. Groundwater level (GWL) in the area of operation of the Kilchen irrigation system main canal (average annual data).

In order to assess the hydrogeological and meliorational state of the sites in relation to the depth of the subsoil, it is necessary to determine their critical depth of the subsoil. The critical depth of the groundwater level is determined by two methods: according to the R. O. Bayer's method – determined by mineralization and the type of the groundwater chemical composition [11]; according to the V. A. Kovda's method [12] – calculated using the formula:

$$H_{kr} = 170 + 8 \cdot t\,(cm)\,, \tag{1}$$

where t – is the average annual air temperature.

According to the R. O. Bayer's method, with a sulfate type of soil and mineralization of groundwater up to 3 g/l, the maximum value of the groundwater critical level occurrence is 1.5 m.

The average annual air temperature for the Dnipro region is 9.2 °C, therefore according to the formula of V. A. Kovda, the maximum value of the critical level of groundwater is: $H_{kr} = 170 + 8 \cdot 9.2 = 2.4\,(\mathrm{m})$.

In 2010, with the lowest amount of precipitation and the highest average air temperature according to average annual indicators, an unsatisfactory hydrogeological and reclamation condition was observed in the territory of the irrigation system. The level of groundwater above the critical level (2.4 m) occupied 51% of the territory around operation of the Kilchen irrigation system, of which 30.7% exceeded the critical depth of the groundwater level above 1.5 m. The rise in the level of groundwater led to flooding of the territories of the Ulyanivka village and the Chumaki village and the rise of the water level in Lake "Ozerishche", which caused the basements of buildings in these settlements to be filled with water. There was a pull-up of salts from mineralized groundwater in these territories, which prompted the processes of salinization and salinization.

Areas with an unsatisfactory hydrogeological-ameliorative state of irrigated lands include areas with a depth of GWL above the critical level for their mineralization of more than 1 g/l, and areas with an average degree of salinity or an average degree of soil salinity.

Areas with a satisfactory hydrogeological and meliorational condition of irrigated lands include areas with a depth of GWL from critical to 5 m with mineralization of more than 1 g/l, and areas with a weak degree of salinity or a weak degree of soil salinity.

Areas with a good hydrogeological and meliorational condition of the land include areas with a depth of groundwater level above the critical level with good natural or artificial drainage and fresh water, as well as areas with non-saline and non-saline lands.

In 2010, 42% of the territory was in an unsatisfactory reclamation state due to the high level of groundwater (above 1.5 m) and the establishment of an average degree of salinity on an area of 52 hectares, while in 2018 and 2021, the ecological and reclamation state changed significantly towards improvement. Climatic indicators during this period were characterized by a slight increase in the average annual air temperature and a significant increase in the amount of precipitation – by 58-60% of the average long-term values. The specified amount of precipitation was extremely unevenly distributed throughout the year and was showery in nature. Despite the increased amount of atmospheric precipitation at that time, the stabilization of GWL was noted due to their redistribution over the surface by horizontal spreading and weathering.

In 2018 and 2021, a decrease in the groundwater level was observed in all observation wells. The terrain in the area of observation well 18 is of concern. The rate of groundwater level rise per year is 0.3 m. It was necessary to calculate the time of groundwater rise to the critical level. If such a trend is maintained, the time for the groundwater level to rise to critical values is determined by the formula:

$$t = \frac{Hp - Hkr}{\triangle h}, \tag{2}$$

where H_p – groundwater level before irrigation; H_{kr} – critical depth of the groundwater level, m; $\triangle h$ – the amount of groundwater level rise per year, m.

The time for groundwater to rise from the level of 5 m according to formula (2) to the critical level of 1.5 m is 11 years and 7 months, and the rise to the level of 2.4 m is 8 years and 8 months (figure 4).

Predicting the mineralization level of groundwater when it reaches the critical depth is achievable by determining the average mineralization of the water layer upon reaching a certain level of groundwater [13]. This calculation depends on the infiltration of irrigation water and atmospheric precipitation as per the formula

$$C = \frac{C_0 \cdot h_0 + C_n \cdot h_n}{h}, \mathrm{g/l} \tag{3}$$

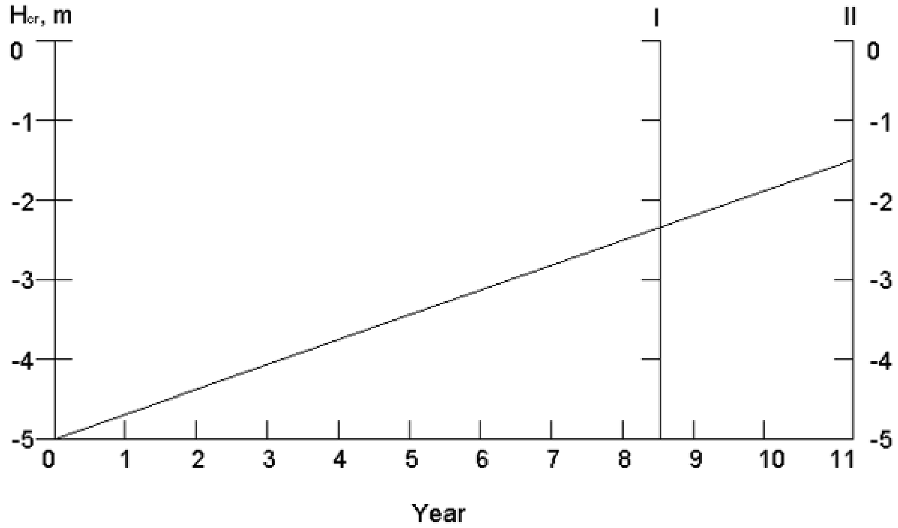

Figure 4. The time prediction of reaching the critical level of groundwater at observation well 14.

where C – average mineralization of the groundwater layer, g/l; C_0 – mineralization of the water infiltration layer, g/l; h_0 – layer of the infiltration water, m; C_n – mineralization of the solution in the pores squeezed out of the aeration zone, g/l; h_n – a layer of natural moisture squeezed out of the aeration zone, m; h – the height of the groundwater level rise during the t period, m.

The mineralization of the water infiltration layer is determined by the formula

$$C = \frac{N_{precp} \cdot M_{precp} + N_{irr} \cdot M_{irr}}{N_{precp} + Nirr}, \text{g/l} \quad (4)$$

where N_{precp} – the total rate of atmospheric precipitation for the t period, m^3/ha; M_{precp} – mineralization of precipitation, g/l; N_{irr} – total irrigation rate for t period, m^3/ha; M_{irr} – mineralization of irrigation water, g/l.

The mineralization of the solution in the pores, squeezed out of the aeration zone, is determined as follows

$$C_n = \frac{C_a \cdot 1000}{W \cdot Wg}, \text{g/l} \quad (5)$$

where C_a – the average content of salts in the soils of the aeration zone, %; 1000 – conversion factor; W – relative humidity of the soil, %; W_g – hygroscopic soil moisture, %.

The typical water mineralization for the Kilchen irrigation system is 2.31 g/l. In 2021, based on climatic indicators, the total atmospheric precipitation rate was 6810 m^3/ha with a mineralization level of 0.02 g/l. “Agro-Kompaniya” LLC requires a total irrigation rate of 13,650 m^3/ha, resulting in a mineralization of the infiltration layer of water at 1.55 g/l. The relative humidity of the soil for Agro-Company LLC ranges between 24-26 %, with hygroscopic humidity at 5 % and an average salt content of 0.24 %, leading to a mineralization of the solution in the pores squeezed out of the aeration zone at 2 g/l. The predicted mineralization for a 2.1 m layer of infiltration water and a 1.1 m layer of natural moisture squeezed out of the aeration zone at a groundwater level rise of 2.4 m is 2.27 g/l. As a result, the mineralization of groundwater is expected to decrease from 3.5 g/l to 2.27 g/l between 2021 to 2029.

The meliorative state of irrigated lands in 2021 with a total area of more than 13,000 hectares is divided according to the relevant criteria into 12.000 hectares – favorable, 1.200 hectares – satisfactory, about 50 hectares – unsatisfactory due to the manifestation of salinization processes.

As of spring 2021, out of the 9.683 ha of soils studied, 8.409 ha are non-saline, 1.236 ha are slightly saline, and 38 ha are moderately saline, while all soils were non-saline in the same area in 2003.

The following studies of the ecological and reclamation state of the Kielce irrigation system in 2021 showed the processes of the groundwater level stabilization and the absence of a systematic rise of it to a critical level compared to what was observed in 2010. It is necessary to pay attention to the territory with an underground water level of 2-3 m (302 hectares of area) and land in LLC "Agro-Kompaniya", where no general tendency to decrease the underground water level was observed.

4. Conclusions

In order to improve the ecological and remedial the soils condition of the Kilchen irrigation system, it is proposed to carry out systematic control of the groundwater level. Increased attention should be paid to monitoring the observation well 14, which is located on the lands of Agro-Company LLC. On irrigated areas, it is necessary to control the irrigation regime of agricultural crops in accordance with the groundwater level in those places where it reaches the level of 2-3 m, and to maintain the humidity of the soil arable layer at the level of 80-85% the lowest moisture content of the soil. It is recommended to carry out chemical reclamation measures on saline areas by applying phosphogypsum at the rate of 3 t/ha under plowing in the fall once every 3 years.

It is worth noting that over the last decade, the groundwater level in the area of operation of the Kilchen irrigation system has decreased significantly. The main reasons for this are a change in climatic conditions with a tendency towards dryness, as well as a decrease in water consumption. Nowadays, several times less water resources are pumped through the main channel than is provided by its design indicators.

The calculated critical depth of the groundwater level according to the method of R. O. Bayer is 1.5 m, and according to V. A. Kovda – 2.4 m. The estimated time to reach the critical level of groundwater is about 9-11 years. Taking into account the constant decrease in water consumption volumes, this indicator can be significantly reduced for a period of more than 20 years. The main chemical composition of groundwater is characterized as sulfate and sodium-calcium with total mineralization in some areas from 0.6-0.9 to 1.7-3.5 g/l. Based on the forecasting results, groundwater mineralization is expected to decrease from 3.5 g/l to 2.27 g/l between 2021 and 2029.

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