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Long-term Changes in the Stability of Agricultural Landscapes in the Areas of Irrigated Agriculture of the Ukraine Steppe Zone

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ABSTRACT
Spatio-temporal assessment of the sustainability of agricultural landscapes over a long period (1892–2020 – 130 years) was carried out on the basis of archival spatial data for the territory of the Dnieper district of the Tauride province and modern data from the State Agency for Water Resources of Ukraine. Taking into account the historical patterns of the development of agriculture on the territory of the Dnieper district and the results of spatial modeling in 1892, territories with low (4.1 thousand hectares – 0.3% of the total area) and medium (310.3 thousand hectares – 23.8%) level of sustainability of agricultural landscapes, which are located in the lower reaches of the Dnieper, were identified. However, the large-scale development of the territory for agricultural land and the development of irrigated agriculture have led to the activation of land degradation processes, soil fertility and the deterioration of the stability of agricultural landscapes over large areas. As a result of spatial modeling, the state for 2020 in the irrigation zone recorded significant areas of agricultural land and adjacent territories with low (179.1 thousand hectares – 13.7% of the total area) and medium (419.0 thousand hectares – 32.1%) stability level. A comparative analysis of the stability of agrolandscapes for two time periods (1892 and 2020) showed that large-scale agricultural land development and an imbalanced land-use culture lead to constant and almost irreversible processes of reducing the stability of agrolandscapes in the areas of irrigation reclamation.

Keywords: irrigation, sustainability, agricultural landscape, groundwater level, climate, fertilizers, export potential, national security.

INTRODUCTION

In the context of global climate change and effective economic activity of land users in the Steppe zone of Ukraine, the use of irrigation reclamation is an urgent issue to obtain high yields of agricultural crops (Lisetskii et al. 2016, Beznitska 2017, Pichura et al. 2019). With their beginning, there were changes in the conditions for the functioning of all natural environment components, in particular, the direction and speed of soil processes changed (Volobuev 1974, Rasmussen et al. 2007, Lisetskii et al. 2016, Dudiak et al. 2019). The results of these changes can have both a positive effect (improvement of moisture supply, increase in productivity, etc.) and a negative one (the processes of flooding, salinization, alkalization, waterlogging, leaching of nutrients into the lower soil profile, which is difficult for plants to reach, and an increase in the amount of nutrient removal with the harvest) (Petrichenko et al. 2013, Martsinevskaya et al. 2018). The direction and intensity of the manifestation of negative phenomena on agricultural and adjacent lands depend primarily on the climatic and hydrological conditions of the region, as well as the volume of irrigation water supply (Pichura et al. 2018).

Extensive use of land resources has led to an imbalance in the natural state of soil fertility, significant deterioration of their fertility, disruption of the ecological balance of the environment, reducing the efficiency and speed of natural soil-forming processes, increasing energy costs for stable crop yields (Dudiak et al. 2019, Mayovets et al. 2021, Vdovenko et al. 2022). The area of lands with a high degree of degradation in Ukraine is more than 1.1 million hectares, most of them in the steppe zone. In particular, the low culture of agriculture leads to a violation of technology and timing of tillage, protection of plants from weeds, pests and diseases, which negatively affects the reproduction of soil fertility (Dudiak et al. 2020, 2021). This exacerbates the problems of humus, agrophysical and reclamation conditions and leads to a decrease in soil fertility as well as environmental safety of land use (Terhoeven-Urselmans et al. 2010, Fagnano et al. 2012, Pichura et al. 2021). Intensification of agricultural production, application of chemicals, reclamation and mechanization leads to a decrease in the content of humus in the fertile soil layer and the deterioration of its ecological, agrochemical and physical properties (Luo et al. 2018, Li et al. 2020, Pichura et al. 2021). Therefore, it is important to determine the spatial and temporal patterns of differentiation of soil degradation processes in order to develop adaptive environmental measures for environmentally friendly land use based on adaptive landscape, basin and geosystem principles (Lisetskii et al. 2014, Pichura et al. 2017).

Considering the current state of irrigated agriculture in the Steppe zone of Ukraine, the unsatisfactory technical level of a significant part of irrigation systems, as well as the level of resource and technological support for both irrigation and growing crops on irrigated lands, it can be argued that there is a high potential danger of developing negative processes and phenomena (Pichura et al. 2015, Ukrainskiy et al. 2020). Therefore, the works related to the study of the irrigated lands state are of particular importance both in terms of the timely determination of negative processes and phenomena, and in order to determine the actual ecological and agro-ameliorative state and sustainability of agricultural landscapes. They should become the basis for the development and implementation of a set of measures to improve the condition and increase the productivity of irrigated and adjacent lands.

Long-term assessment and forecasting of groundwater levels, as well as determining the resistance to flooding of agricultural landscapes in the areas of long-term irrigated agriculture is the main indicator of the influence of climatic and anthropogenic conditions in the irrigation zone of the Steppe of Ukraine (Medvedev et al. 2006, Breus et al. 2019, 2020). The analysis of flooding and its occurrence is the main component of the reclamation regime, which affects the formation of fertility indicators of irrigated lands and, accordingly, the crop yield (Domaratskiy et al. 2018, 2020).

The purpose of the research was to determine long-term changes in the stability of agricultural landscapes in the areas of irrigated agriculture in the Steppe zone of Ukraine (on the example of the south of the Kherson region).

MATERIAL AND METHODS

Spatial and temporal assessment of the stability of agricultural landscapes over a long period (130 years) was carried out on the basis of archival spatial data for the territory of the Dnieper district of the Taurida province (Fig. 1), which included the location of observation wells (135 stations), groundwater level marks. In addition, modern data from the State Agency for Water Resources of Ukraine, the Kakhovka hydrogeological and reclamation expedition, and radar topographic surveys for a digital elevation model construction (DEM) were used.

Spatio-temporal research, modeling and forecasting of the stability of agricultural landscapes, determination of long-term regularities in the formation of the main parameters of climatic conditions (air temperature, amount of precipitation) and anthropogenic load on the territory of the Dnieper province were carried out using the methods of multivariate statistics and geostatistical analysis. Time series and forecasting (TSF) work modules of the STATISTICA 10.0 software product were used for temporal analysis. For spatial modeling, the method of the radial basis function of the Geostatistical Analyst module of the ArcGis 10.1 program was used.

On the basis of many years of original research on assessing the stability of agrolandscapes (Pichura et al. 2014), depending on the levels of groundwater occurrence (GWL), the following classification of qualitative conditions was proposed: *low* *stability* of agrolandscapes – these are areas that are characterized by constant flooding at the beginning and end of the growing season or have a high risk flooding (GWL < 2.0 m), and are also subject to the active manifestation of the processes of salinization and solonetzization of soils; *medium stability* – these are territories that are partially subject to flooding and with significant amounts

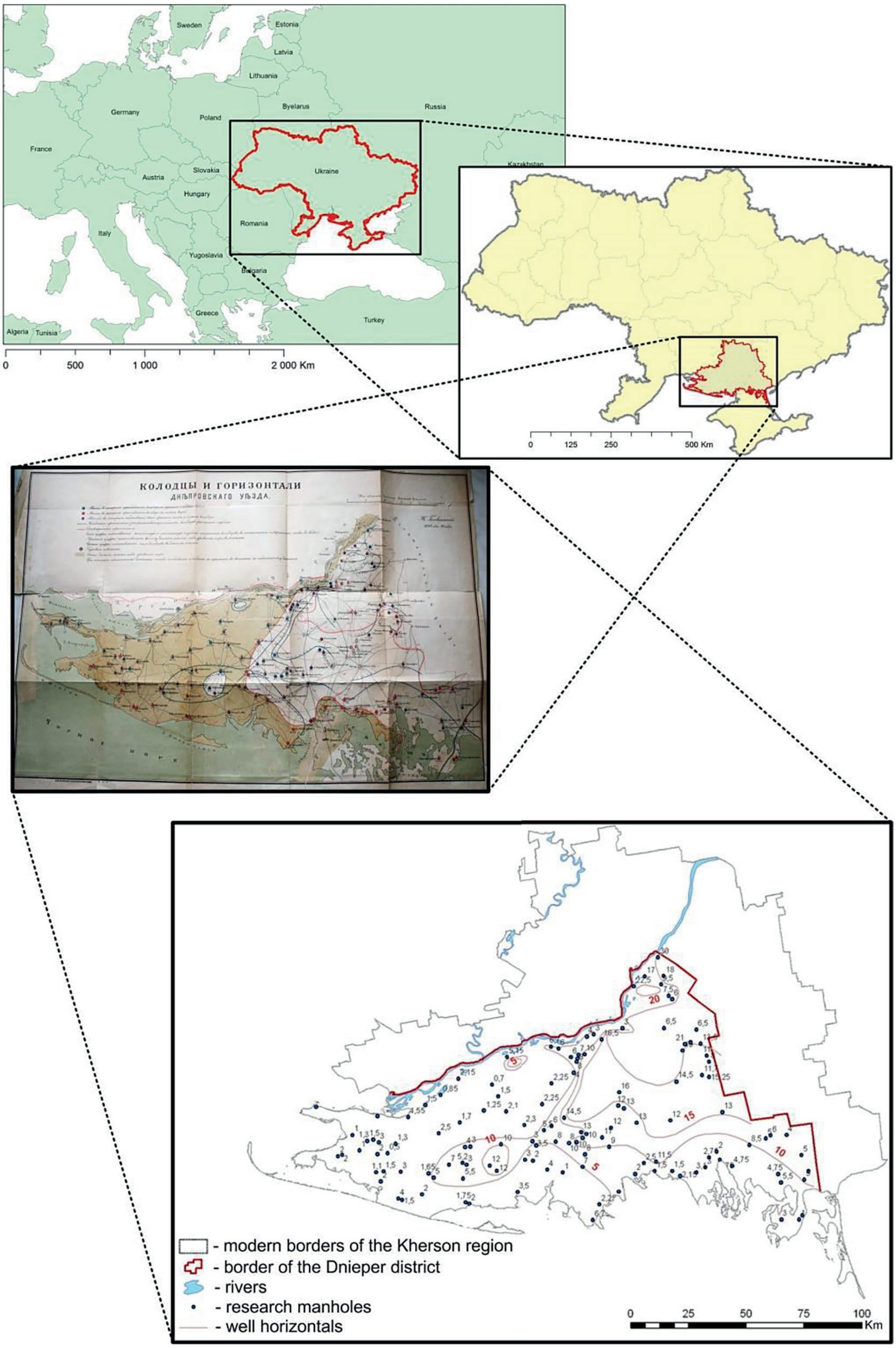

Figure 1. Spatial arrangement of research manholes with marks of groundwater levels in the territory of the Dnieper district of the Tauride province. Initial data – archival materials of N. Golovkinsky (1892)

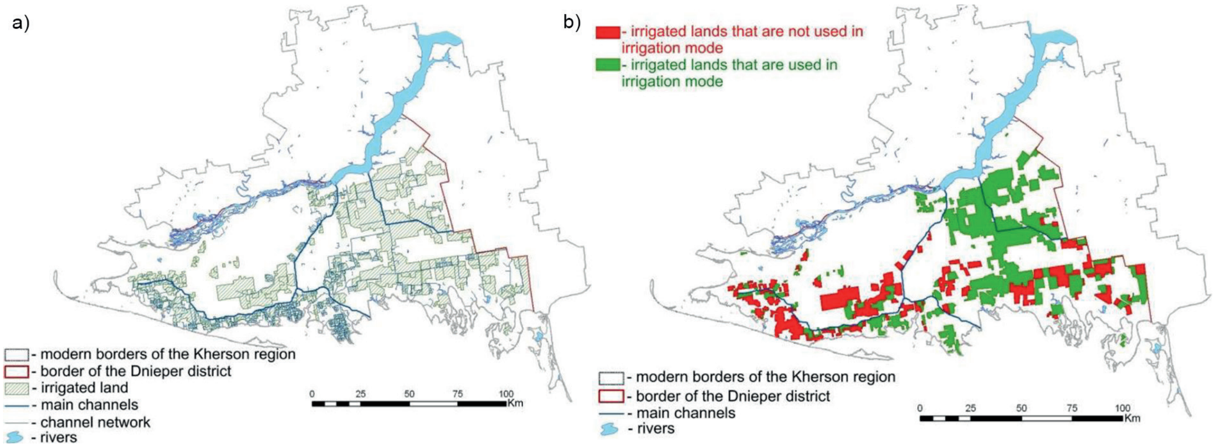

Figure 2. Modern transformation of agricultural landscapes in the south of the Kherson region by irrigation reclamation (within the boundaries of the former Dnieper district): (a) distribution of the hydraulic network; (b) distribution of irrigated lands and their use

of precipitation (for the dry steppe zone more than 400 mm per year and more than 250 mm during the growing season with intensive irrigation) have a risk of raising the GWL to 2.0 m (GWL – 2.1–5.0 m), which also leads to the formation of soil degradation processes; *high stability* – these are territories that are not subject to flooding by groundwater and, accordingly, the processes of salinization and *alkalinity* of soils (GWL > 5.0 m).

RESULTS AND DISCUSSION

For the base period of the conducted research (1892), the Dnieper district was part of the Taurida province, its total area was 11,470.5 square versts, i.e. 1305.5 thousand hectares. As of 1892, the total plowing of the county was 24.0–26.0% (313.0–340.0 thousand hectares), the main cultivated crops were spring wheat, rye, barley, corn, and soybeans. Nowadays, this territory (the south of the Kherson region of Ukraine) is plowed by 60.0% (723.0 thousand hectares), the main cultivated crops are winter wheat, barley, sunflower.

In the entire Kherson region, the area of irrigated land is about 426.4 thousand hectares, which is one fifth of all agricultural land in the region, including: Kakhovka irrigation system (243.1 thousand hectares), North Crimean Chanal

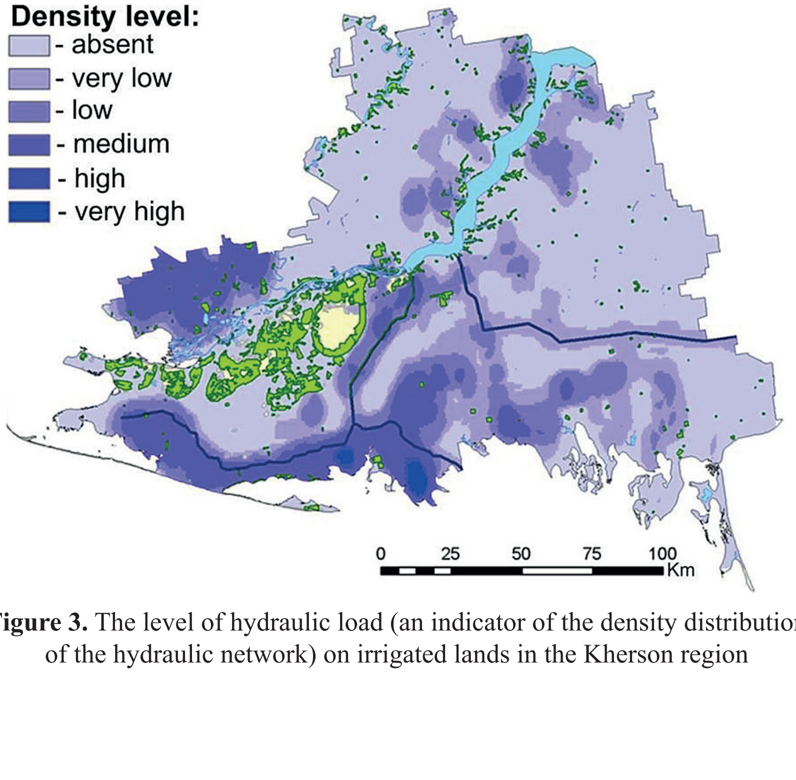

Figure 3. The level of hydraulic load (an indicator of the density distribution of the hydraulic network) on irrigated lands in the Kherson region

and Krasnoznamensk irrigation system (102.0 thousand ha), Ingulets irrigation system (18.2 thousand ha), local irrigation systems – 21.2 thousand ha, local irrigation – 40.7 thousand ha, areas of irrigated land use for 2003–2020. amounted to 250.0–315.0 thousand hectares. The constructed irrigation systems, the main part of which is located within the boundaries of the former Dnieper district, is 70.0% of the entire irrigated territory of the Kherson region (Fig. 2) and they are the largest type of anthropogenic load on the agricultural landscape, an indicator of which can be the density of their distribution, spatial differentiation of groundwater levels and land resistance to flooding.

The irrigation load for the entire territory of the Kherson region was determined by spatial modeling of irrigation canals density using the Line Density of Spatial Analyst tool, which made it possible to identify the spatial patterns in the distribution of hydraulic load (an indicator of the density distribution of the hydraulic network) on irrigated lands in the range of 0–100% (Fig. 3, Table 1).

High and very high hydraulic load was noted on an area of 5.8 thousand hectares (1.36% of the area of irrigation of the Kherson region); the area with an average level of load is 118.6 thousand hectares (27.84%), most of which are located in borders of the former Dnieper district. A low level of load is recorded on an area of 121.54 thousand ha (28.53%), 180.06 thousand ha (42.27% of the area of irrigation of the Kherson region) is characterized by a very low load.

The load on the distribution density of the hydrotechnical network in the agricultural landscapes of the Kherson region increases significantly from north to south and from east to west, which determines the distribution of the area of irrigated lands with different levels of groundwater.

There are large areas of free-flowing sands, the so-called Oleshky sands, in the western half of the study area. They start from the city of Kakhovka and stretch intermittently down the Dnieper and the estuary to the Kinburn Spit. The area of sands amounted to 161.2 thousand hectares, and taking into account the gaps not covered with sand, – 210.0 thousand hectares. The "Journal of General Useful Information" for 1837 indicates that the area of forests on the sands of the lower Dnieper, which in 1802 amounted to more than 5000 hectares, by 1832 fell to almost zero. Experimental work on fixing flying sands began at the end of the 18th century, but they acquired a systematic large-scale character in 1830–1840 in connection with the intensification of works on artificial afforestation. However, the period of general surveying and allotment of land to peasants, which lasted about 30 years (1859–1890), turned into a disaster for forests, including plantations on the sands of the Lower Dnieper. According to Bulatovich (1887), many wooded areas of sands were converted „to their original state" (Popov et al. 1997). The history of afforestation on the Oleshky sands was divided into two stages: protective and reclamation and forestry. At the first century-old stage, the main goal of the work was to fix the sands and create conditions for intensive agriculture: horticulture, viticulture, tobacco cultivation, etc. The second stage of the Lower Dnieper sands development began in the late 1940s. The dynamics of the Kherson region forests in the period from 1956 to 1988 can be traced according to the materials of periodic forest fund surveys. In 1956, the area of the State Forest Fund (SFF) of the region was estimated at 111 thousand hectares, of which less than 10.0% (9.2 thousand hectares) was covered with forest. From 1956 to 1966, about 70.0 thousand hectares of sandy lands were transferred to the SFF, after which its total area remained practically unchanged. At the cost of huge efforts and expenses, over 32 years

Table 1. The hydraulic network placement density on Kherson region agricultural lands

Density of hydraulic network placement, %		Agricultural lands			
		Total		Including irrigated land	
		Thousand ha	%	Thousand ha	%
Absent	< 5.0	1544.99	78.35	–	–
Very low	5.1–10.0	180.06	9.18	180.06	42.27
Low	10.1–20.0	121.54	6.17	121.54	28.53
Medium	20.1–60.0	118.61	6.02	118.60	27.84
High	60.1–70.0	2.48	0.13	2.48	0.58
Very high	70.1–100.0	3.31	0.17	3.31	0.78
Total		1971.0	100.0	426.0	100.0

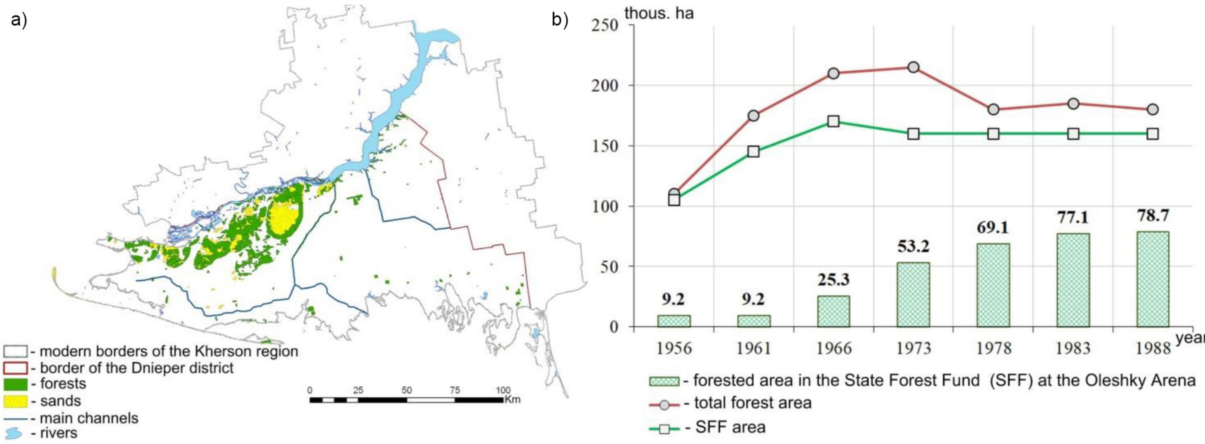

Figure 4. Location of Oleshky sands (a) and dynamics (b) of their afforestation

(1956–1988) the forested area was increased by 8.6 times – from 9.2 to 78.7 thousand ha (Fig. 4). This contributed to the large-scale consolidation of the sands distribution and intensively transpiring forest vegetation, depleting soil moisture, contributed to a decrease in the level of groundwater and a reduction in flooding areas. However, on the Lower Dnieper sands there are numerous shallow depressions, the afforestation of which is still an unresolved problem. Currently, the prospects for forest reclamation of sands are assessed not only in environmental and economic terms, but also in ecological terms.

One of the most significant manifestations of the anthropogenic impact on the regional geosystem of the Kherson region is the transformation of the ecosystem of the Dnieper River (Pichura et al. 2017, 2018), associated with the disruption of relationships between abiotic and biotic components. As a result of large-scale hydrotechnical construction, the river regime of the river was artificially transformed into a lake regime, which led to a sharp slowdown in water circulation and the appearance of extensive zones of stagnation. Although the creation of the reservoirs of the Dnieper cascade and the Kakhovka hydroelectric power station made it possible to significantly increase the water resource and energy potential of Ukraine, it had a negative impact on the environment, especially the lower reaches of the Dnieper, causing a decrease in the river flow, a rise in the level of groundwater, especially in the coastal part, an increase in the volume of underground runoff, an increase in the level of groundwater pollution, and increased abrasion of the coastal zone.

To determine the general patterns of temporal formation of climatic conditions for the period of the 19th–21st centuries, the actual values of meteorological data were converted using the "4253H filter" (Fig. 5). This filtering method makes it possible to obtain a smoothed series, while maintaining the main characteristics of the original series. As a result of the analysis, significant differences in climatic conditions were determined for two qualitatively different periods of farming. Throughout the entire time period of change in the average annual air temperature, a positive trend component is observed, the extremum of which coincides with the beginning of the 21st century, and long-term cycles of different dimensions are also observed in the formation of humidification conditions with a positive trend component of the process, starting from the middle of the 20th century.

Compared with the end of the 19th century, by now the average annual temperature has increased by 3.0 °C (from 9.0 °C to 12.0 °C), the amount of annual precipitation has increased by 70.0 mm (from 390 to 460 mm). The steppe zone of Ukraine is referred to the territories of risky agriculture due to extreme climatic conditions, manifestations of drought and wind erosion. Cyclical components of long-term formation of climatic indicators were: air temperature – 8 years, precipitation – 11 years. In particular, the precipitation changes cyclicity in the steppe zone is in the asynchronous pattern of changes relative to temperature. As a result of seasonal analysis, the manifestations of warming during the first 10 months were determined by an average of 2.6 °C, in the period May–October relative to long-term values there is an increase in precipitation by 90.0 mm, which increased the frequency of unproductive moisture and water erosion during the

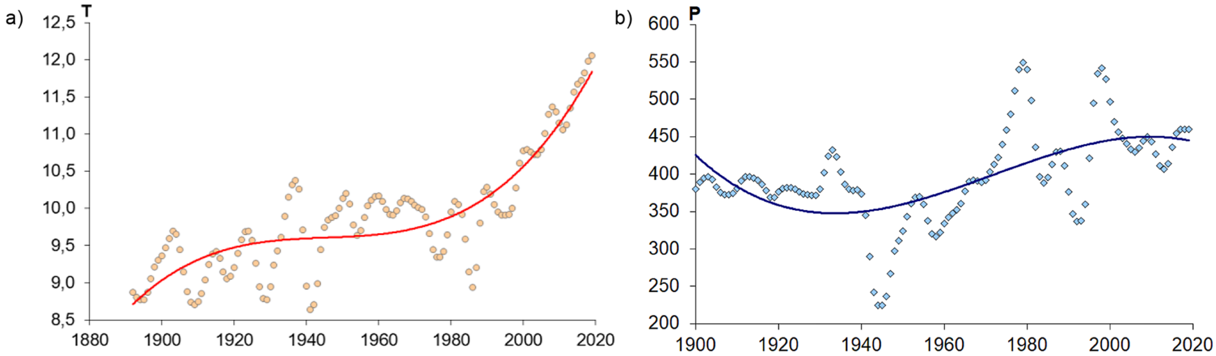

Figure 5. Dynamics of changes in climatic indicators over the period of research (1892–2020): (a) average annual air temperature, °C; (b) – the amount of annual precipitation, mm

growing season. In addition, the main climatic indicator, which significantly affects the rise in the level of groundwater and, accordingly, the change in the hydrological regime of agrolandscapes in the zone of irrigated agriculture, is the manifestation of stormy precipitation.

Using the results of N. Golovkinsky's archive data, a map of the groundwater level in the territory of the Dnieper district as of 1892 was constructed using geostatistical modeling methods. The spatial distribution of the groundwater level varies from 0.5 m (the coastal part and the

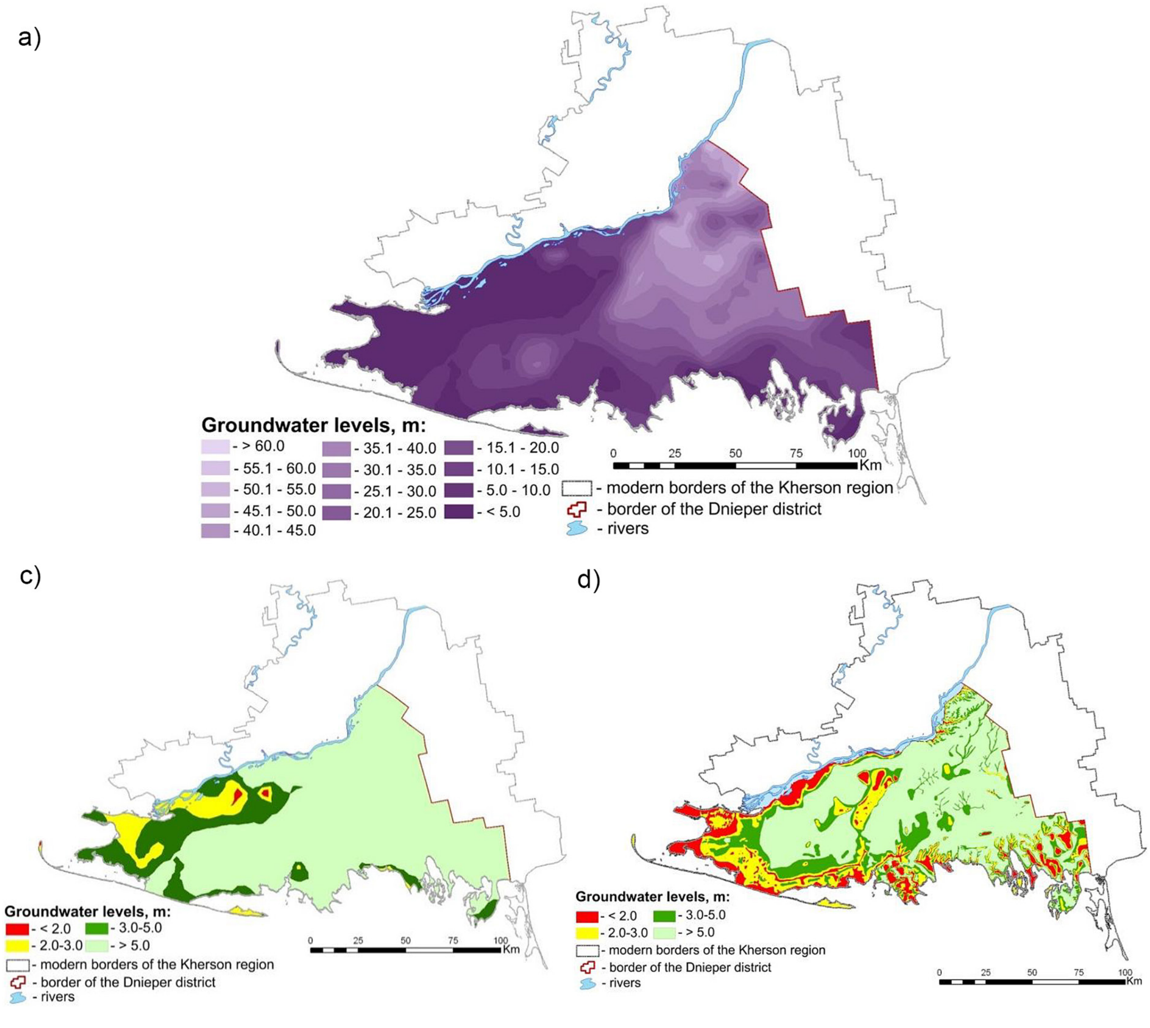

Figure 6. Distribution of groundwater levels (GWL) in the south territory of the Kherson region by irrigation melioration (within the boundaries of the former Dnieper district): (a) spatial differentiation of GWL as of 1892; (b) differentiation of the territory beyond the GWL as of 1892; (c) differentiation of the territory beyond the GWL as of 2020

Oleshky Sands zone) to 65.0 m central and north-eastern part of the study area) (Fig. 6a). On the basis of the constructed maps, the dynamics of the groundwater level, considering the hydrogeological conditions and the DEM of the study area at the end of the 19th and beginning of the 21st centuries. The areas characterized by certain GWL values are determined: 1892 (Fig. 6b): <2.0 m – 4.1 thousand ha (0.3% of the total area), 2.0–3.0 m – 97.9 thousand ha (7.5%), 3.0–5.0 m – 212.4 thousand ha (16.3%), >5.0 m – 991.0 thousand ha (75.9%); 2020 (Fig. 6c): <2.0 m – 179.1 thousand ha (13.7%), 2.0–3.0 m – 174.3 thousand ha (13.4%), 3.0–5.0 m – 244.7 thousand ha (18.7%), >5.0 m – 707.3 thousand ha (54.2%). Over a long period of research under the conditions of climatic and anthropogenic changes, there has been a significant increase in GWL to critical levels in the coastal and near-chanal zones of irrigated areas. At the beginning of the XXI century, due to a 1.4-fold decrease in the area with a groundwater level >5.0 m, an increase in the area with a groundwater level <2.0 m by 44 times, with a groundwater level of 2.0–3.0 m – by 1.8, and with a groundwater level of 3.0–5.0 m – by 1.15 times. A comparative assessment of the territory of the south of the Kherson region over a long period showed a steady pattern of reducing the sustainability of agricultural landscapes (Fig. 7), which is reflected in an increase in the areas with a low level of sustainability by 175 thousand hectares, an average level – by 108.7 thousand hectares and, accordingly, in reducing the area with a high level of stability by 287.3 thousand hectares. Variation in the dynamics of stability of agricultural landscapes over the last 13 years of the 21st century (Fig. 8) was insignificant and amounted to: low level of resistance – 147.0–258.9 thousand ha (V=19.0%), medium – 395.3–434.0 thousand ha (V=3.0%), high – 651.2–756.1 thousand ha (V=4.0%).

With the use of zonal statistics, the spatial pattern of the hydrotechnical network density and the dynamics of groundwater levels were

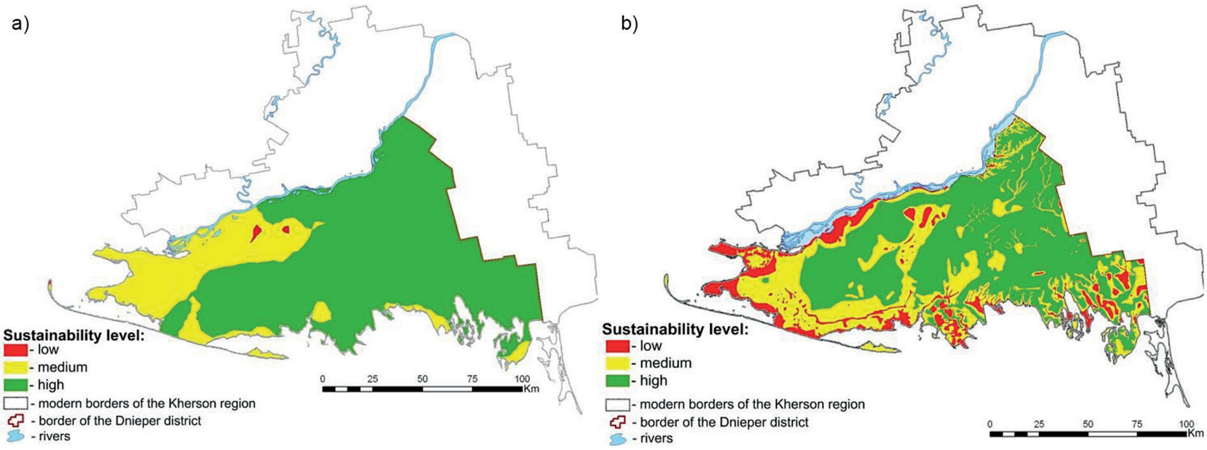

Figure 7. Spatial stability differentiation of agrolandscapes by the level of groundwater occurrence on the territory of the Kherson region within the boundaries of the former Dnieper district, Taurida province: (a) as of 1892; (b) as of 2020

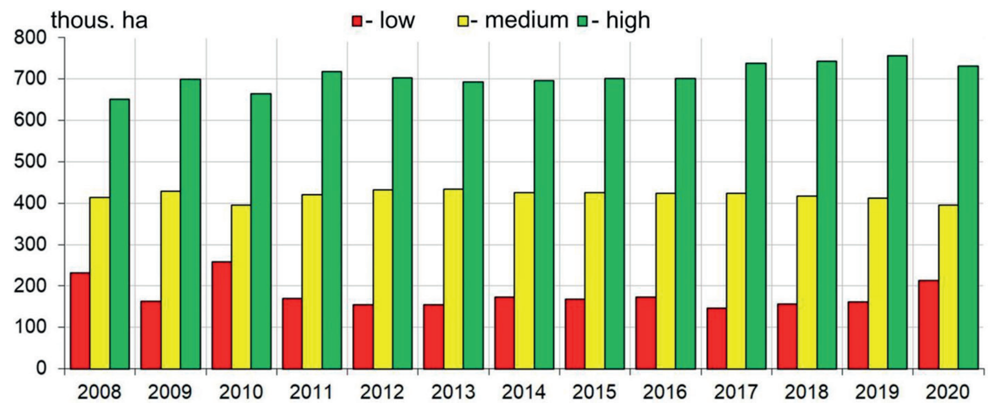

Figure 8. Dynamics of agricultural landscapes sustainability in the Kherson region

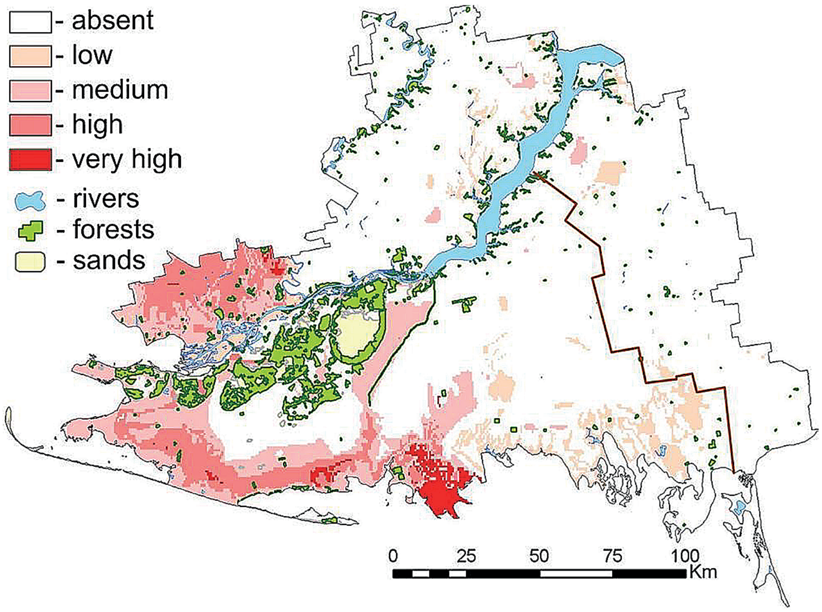

Figure 9. Spatial regularity of the hydrotechnical load influence, taking into account the occurrence of groundwater levels on the agricultural landscape of the Kherson region

determined. This provided an opportunity to clarify the buffer zone and the degree of influence of the hydrotechnical network on the agricultural landscape of the Kherson region (Fig. 9): no or very low load was determined on 73.9% (1457.1 thousand ha) of the territory, low – 6.1% (119.7 thousand ha), medium – 1.9% (234.9 thousand ha), high – 6.8% (134.1 thousand ha), very high – 1.3% (25.3 thousand ha). The largest specific hydrotechnical load, taking into account the occurrence of groundwater levels, was determined within the boundaries of the former Dnieper district; it amounted to 42.3% of its total area of agricultural landscapes: low – 7.5%, medium – 20.3%, high – 11.4%, very high – 3.1%.

As a result of modeling, a direct spatial dependence of the hydraulic network density (anthropogenic load) on the agricultural landscapes stability in the Steppe zone of Ukraine irrigation reclamation was determined, considering the occurrence of groundwater levels.

CONCLUSIONS

As a result of a comparative analysis of the hydrogeological situation for two periods (1892 and 2020), it was found that the stability of agricultural landscapes in the zone of irrigation reclamation of the Steppe of Ukraine is determined by different conditions of climatic and anthropogenic factors influence. Taking into account the historical patterns of the agriculture development in the territory of the Dnieper district and the results of spatial modeling, territories with low (4.1 thousand hectares – 0.3% of the total area) and medium (310.3 thousand hectares – 23.8%) the level of agricultural landscapes sustainability, which are located in the lower reaches of the Dnieper. Low level of agrolandscapes sustainability in the 19th century was caused by massive deforestation in this area. To the date, the spatial and temporal conditions for the formation of agricultural landscapes sustainability have changed dramatically over 130 years. The anthropogenic load on agrolandscapes has increased significantly, which has led to an increase in the sensitivity of agrolandscapes to climate change. An 8.6-fold increase in the area of forest plantations in the area of the Oleshky sands was accompanied by an increase in the stability of the adjacent agricultural landscapes, however, large-scale hydrotechnical construction led to deterioration in the stability of landscapes in the lower reaches of the Dnieper. Large-scale agricultural development of the territory and the development of irrigated agriculture have led to the activation of land degradation processes, soil fertility and the deterioration of the stability of agricultural landscapes over large areas. As a result of spatial modeling, to the date, significant areas of agricultural land and adjacent territories have been recorded in the irrigation zone with low (179.1 thousand ha – 13.7% of the total area) and medium (419.0 thousand ha – 32.1%) level of sustainability. The spatial regularity of the distribution density of the hydraulic network and the dynamics of groundwater levels was determined, which made it possible to clarify the buffer zone and the degree of the hydraulic load influence on the agricultural landscape of the Kherson region. It was determined that within the boundaries of the former Dnieper district, the hydraulic load is 42.3%, incl. low – 7.5%, medium – 20.3%, high – 11.4%, very high – 3.1%. A comparative analysis of the situations of two periods showed that large-scale agricultural land development and an unbalanced land use culture lead to constant and almost irreversible processes of reducing the stability of agricultural landscapes in the areas of irrigation reclamation.

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