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A Study of the Processes of Desertification at the Modern Delta of the Ili River with the Application of Remote Sensing Data

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ABSTRACT

The water regime is the main factor contributing to the formation of landscapes in the river deltas of arid zones, any fluctuations in which lead to a change in the integral hydromorphic landscape. After the construction of the Kapshagai reservoir, the anthropogenic load on the ecosystem of the Ili River delta increased, as a result of which degradation processes, such as drying out and salinization, intensified. In the short term, this phenomenon may lead to the desertification of about 1 million ha of land in the modern river delta. In this regard, the main goal of this study is to look at the processes of desertification in the modern delta of the Ili River, using remote sensing data, which allows for quick identification of the long-term dynamics of degradation processes. For this, the authors used satellite data from Landsat 1–5 MSSS and Landsat 8OLI satellites for 1979 and 2019 and soil analysis data obtained through the ground (field) surveys. Using regression analysis of space and soil data, predictors for interpreting space images were identified and maps of landscape drying and soil salinization were compiled, reflecting the changes that have occurred over the past 40 years. As a result, it was found that in 2019, compared to 1979, the area of landscapes covered with vegetation had decreased by 12% and there was a transformation of hydromorphic landscapes into salt marshes and solonetzes. Over the past 40 years, the volume of non-saline soils has decreased by 41.3% and the volume of saline soils has increased to varying degrees. That is, at present, on the territory of the modern delta, a difficult land improvement situation has developed associated with the cessation of spring and summer floods due to the intensive water use at the Chinese and Kazakh sides.

Keywords: water supply, satellite imagery data, soil salinity, vegetation indices

INTRODUCTION

Land desertification has long acquired a global dimension and is one of the largest challenges for the sustainable development of humanity, causing serious problems of both ecological and socio-economic nature. According to the UN, a third of the Earth's surface is subject to degradation. This is especially true of agricultural lands, where the processes of erosional degradation, dehumidification, depletion of fertility, salinization, waterlogging, acidification, over-consolidation of soils, and an increase in the area of such lands are observed on an ever-larger scale. About 25% of arable land surface worldwide is considered degraded; annually, about 12 million ha are added to the total area of degraded land [UNCSD, 2012].

In Central Asia, including Kazakhstan, the risk of desertification is one of the main environmental and socio-economic problems. In the arid landscapes of Kazakhstan, where it is impossible to imagine the development of agriculture without irrigation of lands, the lands are very vulnerable to impacts, especially in modern conditions of climate change, reduction of water resources, and active anthropogenic development

[Yessenamanova, et al., 2020]. According to the latest data, approximately 76.1% of Kazakhstan's lands are considered areas sensitive to desertification with medium and high sensitivity [Yunfeng, Yueqi, & Yunzhi, 2020]. Therefore, it is very important to quickly determine the location of lands prone to desertification and understand the main causes of desertification to take measures to stop degradation processes in arid zones [Liangliang, et al., 2019]. The implementation of measures to combat desertification is based on land monitoring. Since the advent of aerial and especially satellite imagery, the dynamics of changes in ecosystems have been intensively studied. At the same time, much attention is paid to the development of methods for remote monitoring of lands [Fathizad, et al., 2018; Munkhnasan, et al., 2016; Pankova, & Rukhovich, 1999].

We gained positive experience in using satellite data as a result of the implementation of scientific projects to develop methods for satellite mapping of soil salinity using the example of the Akdala and Shaulder irrigated areas (2012–2015). This experience of many years served as the basis for our research in the Ili River delta [Duisekov et al., 2015; Otarov, et al., 2016].

STUDY OBJECT

The object of our study is the delta of the Ili River, which occupies the southwestern part of the internal-drainage Balkhash depression. The Ili River is a trans-border river between China and Kazakhstan and the main supplier of water to the Lake Balkhash, the largest lake in Central Asia after the drying up of the Aral Sea. The main channel of the Ili River is divided into a fan of deltaic channels diverging to the west and northwest about 105–130 km from the Lake Balkhash. In the north-east, it borders on the ancient delta of the Ili River, in the south Moiynkum and in the north and north-west on the on the water area of the Lake Balkhash (Fig. 1).

The formation of the soil and vegetation cover of the ancient delta is closely related to the history of the formation of the river delta. Some researchers [Dzhurkashev, 1972; Shtegman, 1946] believe that initially, the entire Balkhash depression looked like a sandy desert which the Ili River later invaded and, as a result of increased moisture in the depression, wetland and meadow landscapes were formed. The combination of the desert regime and increased moisture has created an exceptional contrast and diversity of the soil and vegetation cover of the lower reaches.

The location of the region in question in the depths of the Eurasian continent and a significant distance from the seas and oceans determine the pronounced continentality of the climate with characteristic amplitudes of the temperature regime in a seasonal aspect. The hottest month is July, with an average monthly air temperature of +25.4^{0}C, and the coldest month is January, with an average monthly temperature of -13.2^{0}C. The average annual precipitation does not exceed 130–150 mm. The amount of precipitation in a long-term cycle is much less than air humidity. A sharp increase in moisture deficit is noted in early spring. It decreases in autumn, which causes

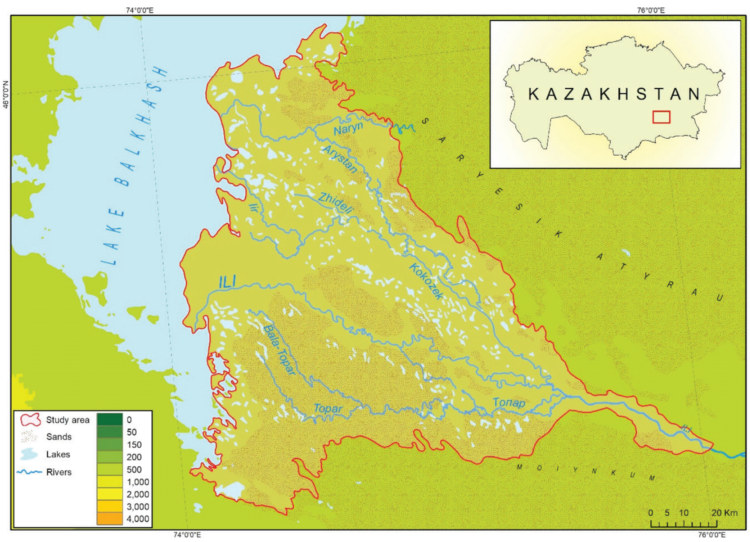

Fig. 1. Map of the location of the object of our study

intense evaporation of moisture from the soil surface and desiccation of the upper part of the profile to an air-dry state. This creates pronounced features of haloxeromorphism in the natural vegetation cover and is reflected in the evolution and transformation of delta soils [Borovskii, 1982; Karazhanov, 1970; Kornienko, Voinova, & Mamutov, 1977].

The main and permanent sources of groundwater supply are seepage waters of the Ili River and the Tasmurun and Akdala irrigation arrays and an underground inflow from the Tasmurun mountains and the sands of the Sary-Ishik-Otrau. The general outflow goes to the north-northwest. The features of the location of the hydrographic network, its hydrological and hydrochemical regimes are important factors affecting the halochemical feature of the landscapes of the lower reaches. The main source of water in the region is the Ili River with the main tributaries Kurty, Kaskelen, Talgar, Chilik, Charyn, etc. It is formed from the confluence of the Kunges and Tekes rivers, which originate in the Tien Shan mountains in China. Currently, the flow of the Ili River is regulated by the Kapchagai reservoir [Starodubtsev, & Truskavetskiy, 2011].

MATERIALS AND METHODS

At the first stage of the study, we developed its structure and created a geoinformation system of the object of study with an appropriate spatially coordinated database using geographical information system (GIS) technologies. For this purpose, we used topographic maps and satellite images from open sources. The currently available topographic maps have not been updated for a long time; therefore, in most cases, the situation on the ground is outdated, especially the numerous delta lakes and channels of the Ili River in the conditions of the modern delta. Therefore, to clarify the situation on the ground, we also downloaded from open sources and used (digitized) high-resolution satellite images. In most cases, we used images from the Landsat satellite, which has a fairly large archive of free images and fairly correctly reflects the current situation [Earth Resources Observation and Science Center (EROS), 2020].

Thus, using cartographic and remote sensing methods, we created thematic layers, such as lakes, rivers, channels, irrigated lands, roads, and settlements, that are an integral part of any information system. Moreover, each layer has the corresponding attribute information, which is in the database of the information system.

In the second stage, we performed a traditional ground survey. These works were necessary to reveal the dependence of the brightness of the pixels of satellite images on the salinity of soils (the main salt-forming ions) of the sub-satellite area. In Figure 2, as an example, we provide a diagram of the location of the subsatellite territory and the location of wells drilling (red circles) for sampling soil at this stage of work.

The survey was carried out using the traditional ground-based method with laying of sections, drilling wells, and taking soil samples from three calculated 0–20, 20–50, and 50–100 cm

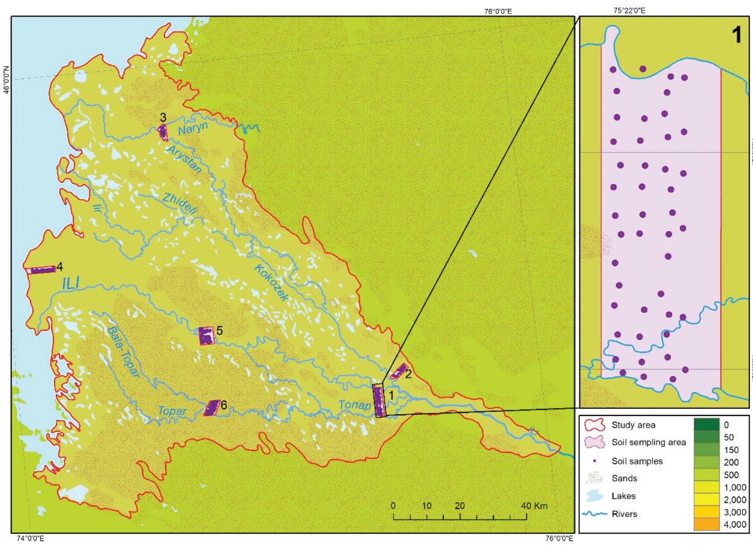

Fig. 2. Sub-satellite sites for the land survey of soils

depths. Fieldwork was carried out using the latest equipment for studying soil salinity and global positioning systems. To refine the soil contours according to satellite images, we used the Garmin 18 global positioning system (GPS) together with an ASUS netbook and to determine the coordinates of the points of sections, we used the Garmin 62s GPS. Ground surveys were carried out following the All-Union Instruction [USSR Ministry of Agriculture, 1973] and the Guidelines for Conducting a large-scale soil survey [USSR Ministry of Agriculture, 1979]. When using space methods, we used the methodology of Pankova and Mazikov [1985] as a basis, supplemented by the works of Pankova's students, D. Rukhovich [2009] and M. Konyushkova [2010]. To analyze the material composition of soils, we used analytical methods, which are detailed in the guidelines for general soil analysis [Arinushkina, 1977].

As a result of the carried-out salt survey of the territory of 7 sites with a total area of more than 21 thousand ha, a total of 566 sections were laid and wells were drilled and 966 soil samples were taken. After the chemical analysis of the selected soil samples, the obtained analytical data were entered into the project database.

The third stage consisted of laboratory research, namely the analysis and interpretation of space images. A large archive of satellite information is needed to monitor soil drying and salinity. We downloaded and applied Landsat images [Earth Resources Observation and Science Center (EROS), 2020].

As shown in Table 1, to interpret the process of drying and salinization of soils, we selected satellite images taken with atmospheric cloudiness of less than 1%. This is explained by the fact that cloudiness is the main factor preventing the deciphering of the study object and the processes occurring in it [Konyushkova, 2010].

We deciphered satellite images to compile a drying map using the "maximum similarity" method, and for the soil salinity map of the study object, we used the "maximum similarity" method and regression analysis of the relationship between the ion-salt composition of soils (traditional water extract) and space survey data [Otarov, et al., 2016]. Regression analysis was performed in the STATISTICA 7.0 software environment. Three groups of predictors were used as independent variables, namely the spectral channels of the Landsat satellite image, vegetation indices describing the state of vegetation, and the ratio of spectral channels. Regression analysis was carried out separately for each studied soil layer (0–20 cm, 20–50 cm, 50–100 cm). These data were used as a basis for identifying desertification processes using the ILWIS v.3.3 application package based on previously specially developed algorithms.

Table 1. Satellite images used

No.	Satellite images	Shooting time	Cloudiness
1	Landsat 1–5 MSS	13.08.1979	0%
2	Landsat 8OLI	05.08.2019	0%

RESULTS AND DISCUSSION

The processes of desertification of hydromorphic landscapes in the Ili River delta, which began after the construction of the Kapchagai reservoir in 1970 and the development of irrigation in its basin, have continued for 50 years, weakening only during flood years. The degree of land degradation is differentiated in space depending on changes in the water regimes of delta landscapes under the influence of anthropogenic pressure. Previous studies showed that in the modern delta of the Ili River, two types of desertification dominate: drying and salinization of soils [Starodubtsev, & Truskavetskiy, 2011]. It was established that these processes are closely related to each other and negatively affect not only the bio productivity of landscapes [Starodubtsev, & Truskavetskiy, 2011; Yunfeng, Yueqi, & Yunzhi, 2020] but also their microbiological activity [Laiskhanov, et al., 2018].

The dynamics of drying of the territory of the modern delta of the Ili River

To determine the impact of the intensive use of water in agriculture and the regulation of the flow of the Ili River as a result of the construction of the Kapchagai hydroelectric power station on the drying up of the delta and to identify the most susceptible to desertification areas of the delta, work was carried out to create thematic layers of the water surface, such as lake systems and river network, surface covered with vegetation and open surface (without vegetation), i.e. sands, salt marshes, takyrs, and other objects at the modern delta of the Ili River.

For decryption, we applied an approach based on automatic image classification with training by the "best likelihood" method. The image classification was carried out in the GIS ILWIS 3.3 software. For this purpose, during the fieldwork, reference areas were selected for each class according to the values of brightness and location.

For this purpose, we used images of 1979 and 2019 from the generated satellite data archive, obtained in early August, when the vegetation cover of the delta is still in an active phase of growth and development, i.e. at this moment, the open surface uncovered by vegetation is quite accurately deciphered. Using the selected Landsat satellite images in the ILWIS 3.3 software environment, maps of the main natural objects (surfaces) of the Ili River were built (Fig. 3).

A visual analysis of the cartographic material shows that over 40 years after the regulation of the river flow, the area of the open (without vegetation) surface has increased quite noticeably (in the figure, they are marked with red circles), i.e. after the regulation of the river flow, the processes of drying and desertification of the territory have begun to prevail in the modern delta. Since recent years, water use has increased rapidly. The total water consumption in the Ili River basin in 2000 was 14.3 km^3/year, in 2005, it equaled 17.2 km^3/year, and in 2014, it amounted to 15 km^3/year. In 2000, China and Kazakhstan consumed 38% and 62% of water, respectively. By 2014, the relative share of water consumption in China had increased to 43% [Thevs, et al., 2017].

Drying and desertification of the territory of the modern Ili River delta are also confirmed by digital data of long-term dynamics of areas, i.e. open and vegetated surfaces of the delta. During the studied period of river flow, the open surface area (without vegetation, such as sands, salt marshes, takyrs, etc.) had increased by 82.8 thousand ha. The areas of water and vegetated surfaces had decreased, respectively, by 3.3 and 79.5 thousand ha.

It should be noted that the drying process of hydromorphic landscapes throughout the delta is uneven. It is highly developed on the territory of the left wing of the Topar system, the Topar-Ili interfluve, and along the main channel of the Ili River and especially in its entry part. Besides, the right bank of the Naryn canal is quite susceptible to drying (desertification) [Starodubtsev, & Truskavetskiy, 2011].

Analysis of satellite imagery data and mapping of soil salinity

The data on the coordinates of the pits laying site, the depth of soil sampling, the content of the main salt-forming ions in the water extract from the soil, the calculated amounts of the sum of salts, the "total effect" (TE) of toxic ions, and other indicators of soil salinity were introduced into the database. This information was reflected in an article previously published by us [Duisekov, et. al., 2015]. During the study, these data were used to develop an algorithm for decoding soil salinity from satellite images.

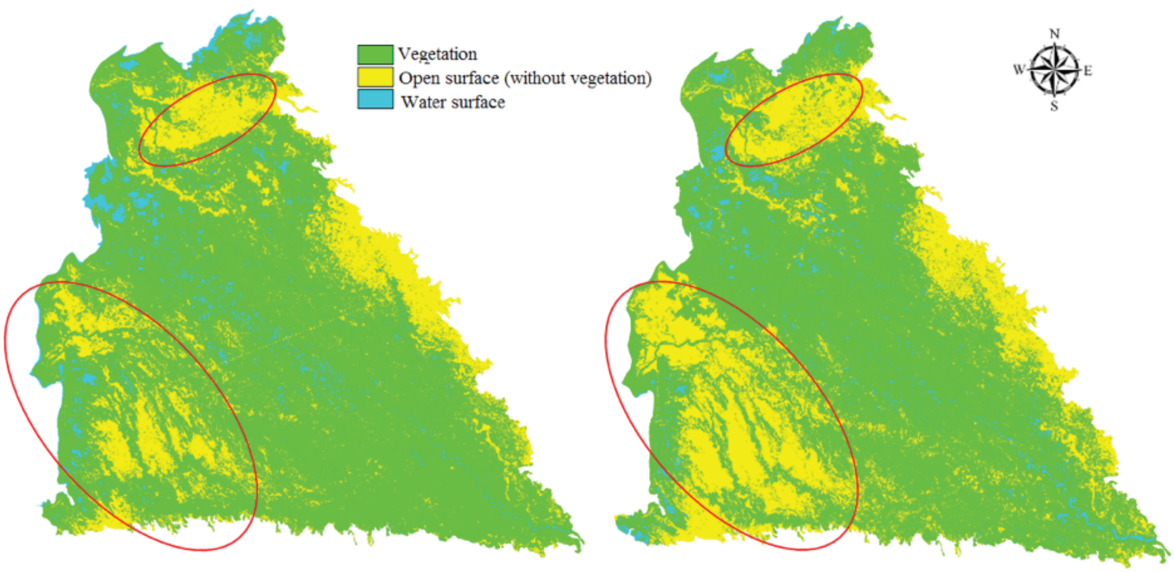

Fig. 3. Dynamics of the area of natural objects (surfaces) of the Ili River delta (1979 – left, 2019 – right)

To compile algorithms for the dependence of the spectral characteristics of the images on the ion-salt composition of soils (regression models) and maps of soil salinity, we used Landsat 8 OLI multispectral images downloaded from open sources with a spatial resolution of 30 m.

The following approach was used to compile soil salinity maps. For points with data from field studies of soil salinity in the GIS, the values of pixel brightness were extracted for all spectral channels of Landsat 8 OLI satellite images, and the values of the pixel brightness ratios in different channels and vegetation indices were calculated. The vegetation index is an indicator calculated as a result of operations with different spectral ranges (channels) of the image and related to the parameters of vegetation in a given pixel of the image [Cherepanov, 2011]. The effectiveness of these indices is determined by the features of the reflection; they are derived mainly empirically. As a result, the following potential predictors of soil salinity were obtained:

The predictors used for the regression analysis can be divided into three groups:

1. Spectral channels Band 1, Band 2, Band 3, Band 4, Band 5, Band 6, Band 7, Band 8, Band 9, Band 10, Band 11.
2. Vegetation indices describing the state of vegetation:

NDVI=NDVI=(Band5-Band4)/(Band5+Band4); IR_R=Band5/Band4; VEGI=Band4-Band3; SQRT= J(Band5/Band4); TND VII= =J ((Band 5-Band4)/(Band5 + Band 4))+0,5; GNDVI=(Band5-Band3)/(Band5+Band3); NDGR=(Band3-Band4)/(Band3+Band4); IPVI=Band5/(Band5-Band4); RVI=(Band5-Band4); NDSI=(Band6-Band5)/(Band6+Band5).

3. Ratio of channels not related to vegetation indices:

B/G=Band2/Band3; R/G=Band4/Band3; B/IR=Band2/Band5; B/SWIR2=Band2/Band6; IR/B=Band5/Band2; SWIR2/G=Band6/Band3; SWIR/SWIR3=Band9/Band7.

To establish the relationship between soil salinity and satellite imagery data, we performed regression analysis in the STATISTICA 10.0 software environment separately for each soil layer under study (0–20 cm, 20–50 cm, 50–100 cm).

As a result of the performed regression analysis, we constructed significant regression models for all layers with the coefficients of determination (R^2) from 0.3 to 0.6. Here, the vegetation index IPVI for the top layer of the canopy turned out to be the best predictors (Table 2).

For the two lower layers 20–50 cm and 50–100 cm the B/IR2 predictors were used. In Figure 4, as an example, we provide a map of the degree of salinity of the upper 0–20 cm soil layer. The convergence of soil contours, compiled using the regression equation and based on the results

Table 2. Results of regression analysis of the relationship between the chemical composition of the soil (0–20 cm layer) and spectral properties of Landsat 8OLI images

Predictors (independent variables)	Connection	Soil chemistry (dependent variables)								
		The total amount of salts	Total alkalinity in HCO^3	Cl	SO^4	Ca	Mg	Na	K	TE of toxic ions, milligram-equivalent C
Band1	absent	-	-	-	-	-	-	-	-	-
Band2	absent	-	-	-	-	-	-	-	-	-
Band3	present	+	-	+	-	+	+	+	+	+
Band4	absent	-	-	-	-	-	-	-	-	-
Band5	absent	-	-	-	-	-	-	-	-	-
Other channels (Bands)	absent	-	-	-	-	-	-	-	-	-
B/IR	absent	-	-	-	-	-	-	-	-	-
B/IR2	absent	-	-	-	-	-	-	-	-	-
IR2/B	absent	-	-	-	-	-	-	-	-	-
NDSI	present	+	+	+	+	+	-	+	-	+
NDVI	absent	-	-	-	-	-	-	-	-	-
IPVI	present	+	-	+	+	+	+	+	-	+
Other	absent	-	-	-	-	-	-	-	-	-

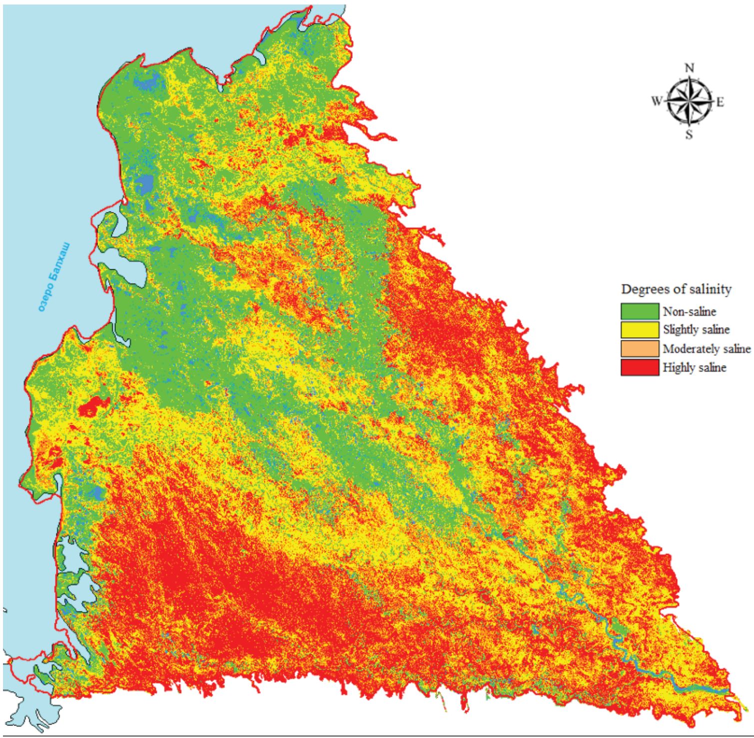

Fig. 4. Map of soil salinity in the modern delta of the Ili River, 2019

of the ground survey, was also satisfactory at the border and amounted to 67.3%.

The main reason for such a distribution of salts over the delta is the practical absence of spring and summer river floods and the subordination of the intra-annual distribution of river flow to the regime of water release from the reservoir. This is primarily due to the construction and commissioning of the Kapchagai reservoir on the Ili river. As a result of regulation, the flow of the Ili River decreased by 25%, which led to a sharp deterioration in the water supply of the entire delta area of the river. Previously, the central part of the delta was flooded mainly during the period of powerful summer floods, while the head part was well watered by early spring floods as a result of mash-and-jam phenomena in the channels. The regime of releases from the Kapchagai reservoir does not provide for large water discharges in the spring-summer period. Therefore, the head and central parts of the delta were the first to dry out. In the Dzhidelinsky system of canals, the reduction in lakes went in two directions. On the one hand, the flowing lakes, intensively silting up, turned into swamps and most of them dried up. On the other hand, as a result of the development of the main channels, smaller lateral canals that fed the lakes of the marginal parts of the system were cut off and dried up [Otarov, 2014; Thevs, et al., 2017].

In support of this, for comparison with the 2019 map, below, we present a map of soil salinity in the delta, compiled from 1979 images (Fig. 5). To map soil salinity in 1979, the same approach and predictors were used as were used to map the situation in 2019. From the soil salinity map of the delta, it can be seen that by 1979, the contours of highly and moderately saline soils had already appeared on the head of the delta due to the cessation of spring floods, which occurred due to jamming phenomena in the channels. As we have already noted, the process of drying and salinization of soils is most pronounced in the Topar and Dzhidelinskaya systems of canals and on the head of the delta. Hydromorphic landscapes with non-saline soils are concentrated along the Zhideli, Kugaly, Ir, and Arystanda canals. A similar distribution of desertified territories in the delta for 37 years after the regulation of the river flow was obtained in [Starodubtsev, & Truskavetskiy, 2011] through space monitoring using NASA/MODIS/Terra space images.

Comparison of areas with different degrees of soil salinity showed that catastrophic changes have taken place in the delta over the past 40 years. The areas of non-saline soils during this time decreased by 386.2 thousand ha, or 41.3% (Fig. 6). During the same period, the areas of slightly and moderately saline soils increased by 2.4% and

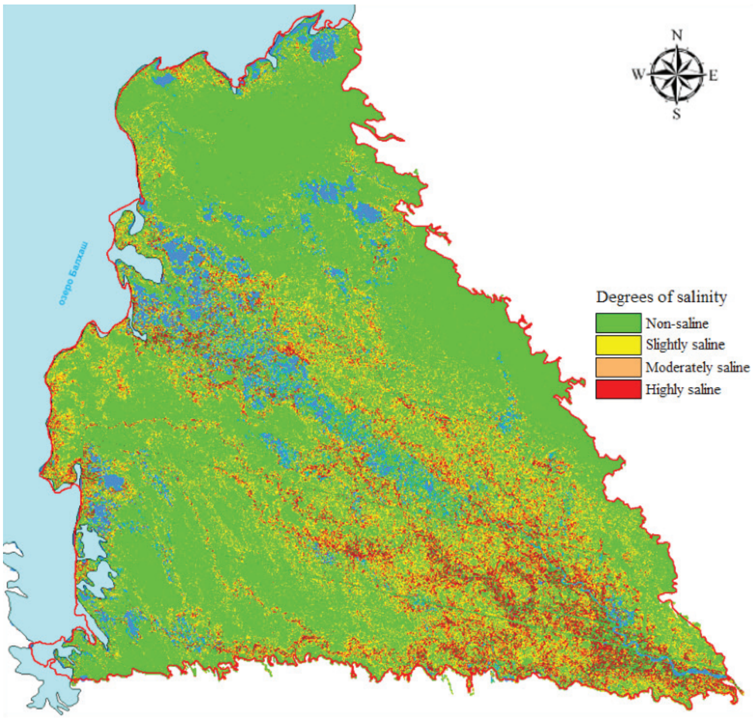

Fig. 5. Maps of soil salinity of the modern delta of the Ili River, 1979

15.7%, respectively. The areas of highly saline soils increased by 21.4%, or 199.9 thousand ha.

Thus, the analysis of the long-term dynamics of soil salinization in the delta and the causes of salinization showed that the main reason for the change in water supply conditions leading to the drying and desertification of the modern delta and soil salinization is the regulation of the Ili River runoff. The areas of saline soils increased quite sharply, which in turn led to a reduction in hydromorphic landscapes with non-saline soils. That is, at present, on the territory of the modern delta, a difficult reclamation situation has developed, associated with the cessation of spring and summer floods. Besides, in the last decade, the ecological situation in the modern delta has become noticeably more complicated due to the expansion of irrigated areas in the Ili River basin from both the Kazakhstan and China sides [Thevs, et al., 2017].

It should also be noted that the water resources for the delta are exactly the nodal link of problem situations, the management of which will allow

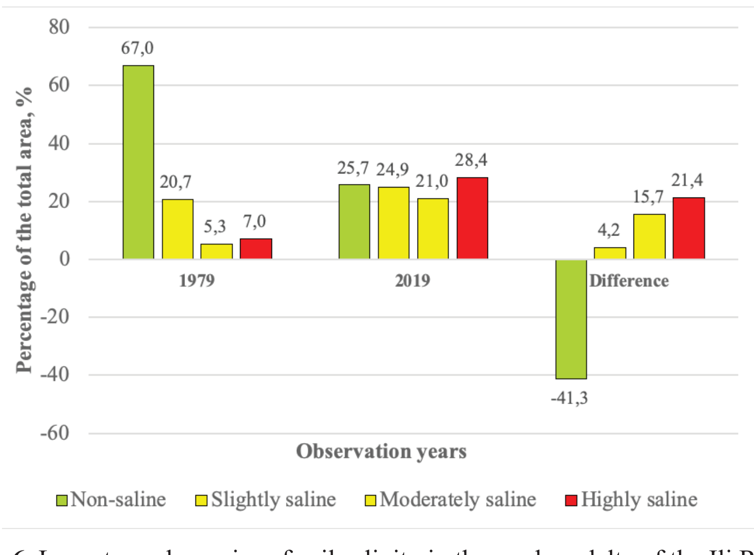

Fig. 6. Long-term dynamics of soil salinity in the modern delta of the Ili River

purposefully changing the degree of soil salinity and the overall ecological situation of the delta.

CONCLUSIONS

The processes of desertification of landscapes in the Ili River delta began after the construction of the Kapchagai reservoir. The degree of land degradation is differentiated in space depending on changes in the water regimes of delta landscapes under the influence of anthropogenic pressure. Previous studies showed that in the modern delta of the Ili River, two types of desertification dominate: drying out and salinization of soils. The study of such phenomena of desertification using data from remote sensing of the Earth is one of the urgent problems of modern time.

Based on the study of the relationship between the spectral properties of the Landsat satellite image and the ion-salt composition (salinity) of soils, we demonstrated the possibility of using them as a deciphering indicator of the degree of soil salinity. The tone of the image in individual channels of satellite images turned out to be insufficiently informative for assessing soil salinity; the ratios of the tones of individual channels of the survey and vegetation indices were most informative. As a result, the contours of saline soils with different degrees of salinity were determined, and then all geographical objects were compiled in the form of a map.

An analysis of the cartographic material showed that the process of drying and salinization of soils was most pronounced in the Topar and Dzhidelinsky systems of channels and on the head of the delta. Hydromorphic landscapes with non-saline soils are concentrated along the Zhideli, Kugaly, Ir, and Arystanda canals.

Comparison of areas with different degrees of soil salinity showed that catastrophic changes have taken place in the delta over the past 40 years. The area of non-saline soils during this time decreased by 386.2 thousand ha, or by 41.3%. During the same period, the areas of slightly and moderately saline soils increased by 2.4% and 15.7%, respectively. The areas of highly saline soils increased by 21.4%, or 199.9 thousand ha. That is, at present, on the territory of the modern delta, a difficult reclamation situation has developed, associated with the cessation of spring and summer floods.

Under these conditions, to maintain and preserve the delta, it is necessary to periodically arrange artificial floods in the delta to flush the soil from salts and replenish the soil moisture.

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