Georgian Geographical Journal

Impact of River Flow Regulation on Deltas in the Black Sea Basin

Georgian Geographical Journal, 2025, 5(1), 15-30

DOI: https://journals.4science.ge/index.php/GGJ

Vladimir Starodubtsev[1], Manoni Kodua[2*], Maryna Ladyka[1]
Vyacheslav Bogdanets[3]

[1] Department of Agrosphere Ecology and Environmental Control, National University of Life and Environmental Sciences of Ukraine, Kyiv.

[2] Department of Hydro-engineering, Georgian Technical University, Tbilisi, Georgia.

[3] Department of Geodesy and Cartography, National University of Life and Environmental Sciences of Ukraine, Kyiv

* Corresponding author: m.kodua@gtu.ge

Citation: Starodubtsev, V.; Kodua, M.; Ladyka, M.; Bogdanets, V. Impact of River Flow Regulation on Deltas in the Black Sea Basin. *Georgian Geographical Journal.* 2025, 5(1), 15-30. https://doi.org/10.52340/ggj.2025.05.01.03

Abstract

The study aimed to analyse the impacts of flow regulation and economic activity on river deltas in the Black Sea Basin (Rioni, Chorokhi, Kizilirmak, Dnieper, Dniester, and Danube). The relevance of this problem is because changes occurring in deltas significantly affect their natural resources and the prospects for their use. A comparative analysis of the deltas of the basin allows us to show the features and scale of changes occurring in them. The main methods used for this investigation were cartography, GIS modelling, and some field expedition routes. Natural conditions, delta morphology, sediment transport, flow discharge, and land use shape the features of delta transformation in these rivers. Erosion processes are observed as sediment accumulates in deltas exposed to coastal currents and waves (Rioni and Chorokhi in Georgia, Kizilirmak in Turkey). River flow regulation by reservoirs has reduced the flow of water into the delta and has decreased sediment influx. Deltas of the Dnieper and Dniester Rivers in Ukraine mostly depend on water releases from reservoirs. It is noticed that both the sea and the river influence the Danube Delta. The results obtained are useful for the construction and operation of infrastructure in deltas; the use of these areas for recreation, agriculture, and forestry; the protection of Ramsar wetlands; and the creation of new human settlements.

Keywords: river delta, Black Sea basin, flow regulation, wetlands, coast.

Introduction

Deltas, which form when rivers flow into oceans, seas, and lakes, are of great ecological and economic importance due to their geographical location and rich natural resources—land, water, and biological. However, in the last century and a half, their natural environment has been undergoing obvious degradation due to the construction of huge hydroelectric power plants and reservoirs and increasing diversion of water from rivers for irrigation, industrial, municipal, and drinking water supply, as well as economic development of the deltas. It is the regulation of river flow and intensive economic activity in their basins that lead to significant changes in the natural environment of river deltas. (Starodubtsev, 2007) This process is becoming global but manifests itself differently, including wetlands desertification (Starodubtsev & Petrenko, 2005; Starodubtsev & Truskavetsky, 2011), depending on the climate of the region, the morphological characteristics of deltas, sediment transport, the volume of runoff and the nature of its regulation, and the intensity of water use and water salinity, as well as several other factors. The conditions in which rivers flow into bodies of water (oceans, seas, estuaries, and lakes) also significantly influence processes in deltas.

The most famous in the last century were the strongest processes of degradation and desertification (we use this term not only for drylands but also for wetlands turning into deserts) in delta landscapes.

The Colorado River is located on the US-Mexico border (Glenn, 1966). Then they manifested themselves catastrophically in Central Asia and rapidly spread to other climatic zones around the world. To study these processes, large scientific schools were formed in the USA (Coleman J.M., Vorosmarty

C.J., Syvitski J.P.M.), in Eastern Europe and Central Asia (Mikhailov V.N., Kovda V.A., Borovsky V.M., Novikova N.M., etc.), as well as many prominent researchers in other regions, including in Georgia, Turkey, Ukraine, Romania, etc., whose works are mentioned in this message.

In the Black Sea basin (Fig. 1), we analyse changes in river deltas flowing into the sea and subject to strong influence of alongshore currents and waves (Rioni and Chorokhi in Georgia, Kizilirmak and Yesilirmak in Turkey), deltas formed in long estuaries (Dnieper and Dniester in Ukraine), as well as the Danube delta, which has a more complex influence of both sea and river.

Figure 1. River basins of the Black Sea: 1 – Danube, 2 – Dniester, 3 – Dnieper, 4 – Don, 5 – Kuban, 6 – Rioni, 7 – Yesilirmak, 8 – Kizilirmak, 9 – Chorokhi

Economic activities in river basins flowing into the Black Sea caused a decrease in water flow into the sea by the end of the 20th century from approximately 381 to 348 km^3, and sediment from 95 to 52.2 million m^3 (Jaoshvili, 2002; Jaoshvili, 1986). And now this process is actively continuing (Mikhailova & Jaoshvili, 1998; Mikhailova, 2009; Berkun, 2015) causing significant changes in land cover in deltas. Other factors influencing the formation of landscapes in the deltas of the Black Sea basin are the economic development of delta plains, including recreational ones, the growth of settlements, and hydraulic engineering construction on the coast and in the water area. Sometimes such factors are even environmental protection measures in the delta itself or in the entire river basin. And, of course, the active erosion and accumulative activity of the water masses of the sea remains.

Methods and Materials

The main methods used for this investigation were cartography, GIS modelling, and some field expedition routes. On the eastern coast of the Black Sea within Georgia, we are considering the deltas of two large rivers, formed in the conditions of Mediterranean-type subtropics in the south (Chorokhi River) and humid subtropics in the central part of this coast (Rioni River) (Tsereteli et al., 2011). The Chorokhi River basin (22,100 km^2) is located mostly in Turkey (91%), and only the lower part of the riverbed and delta (9%) are in Georgia (Fig. 2). Dams and reservoirs classify Chorokhi as highly regulated. In total, it is planned to build 27 hydroelectric dams with reservoirs in its basin (Fig. 3), only one of which is in Georgia on the Adzharistskali tributary. Under such strong regulation by dams, the annual flow of the river decreased from 8.71 km^3 (Jaoshvili, 2002; Jaoshvili, 1986) to 6,824 km^3 (Sezer, 2009), and the sediment runoff, which amounted (Jaoshvili, 2003) to 4,920,000 m^3/year (according to other sources, up to 5.8 million m^3), decreased accordingly, but we did not find exact values in scientific publications. It was noted that of the total amount of sediment, 2,310,000 m^3/year accumulated in the coastal zone, forming a delta and shelf, and 2,610,000 m^3/year was carried out to the sea. It was noted that of the total amount of sediment, 2,310,000 m^3/year accumulated in the coastal zone, forming a delta and shelf, and 2,610,000 m^3/year was carried out to the sea. A rapid decrease in sediment runoff, visible even on satellite images, creates, according to many scientists (Jaoshvili, 1986; Berkun, 2015; Eruz et al., 2005; Hay, 1994; Mikhailova, 2009) a real threat to the ecosystems of the delta, the erosion of the sea edge, and the destruction of the beaches of the city of Batumi.

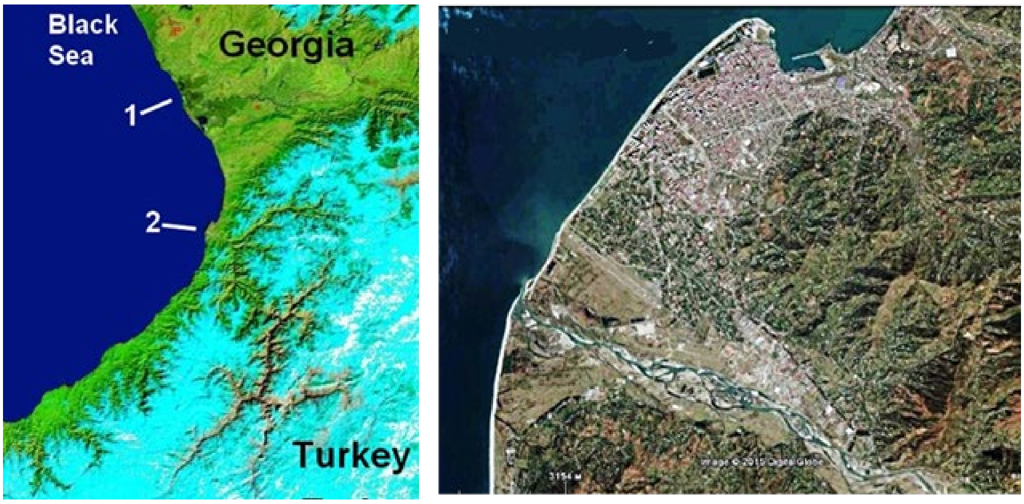

Figure.2. Basin of the Chorokhi (2) and Rioni (1) rivers in winter (left, Terra satellite image) and geomorphological features of the delta (right, Google Earth)

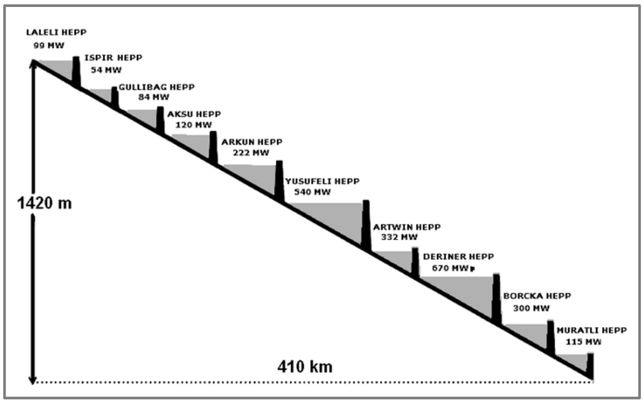

Figure. 3. Placement of dams and hydroelectric power stations on the Chorokhi River (Berkun et al., 2015)

Indeed, the southern and southeastern coast of the Black Sea is characterized by the development of erosion and coastal retreat under the influence of regulation of river flow and sediment accumulation in reservoirs (Berkun, 2015; Hay, 1994; Klaphake & Waltina, 2011; Mikhailova & Jaoshvili, 1998). The manifestation of this process in the Chorokhi River basin and the interaction of land and sea in the Chorokhi delta area became the subject of our research using remote sensing methods. At the first stage of the study, high-quality Landsat-5 and 8 images were used for the period 1980-2015 (Starodubtsev, 2014; Starodubtsev & Basarab , 2017a). And at the second stage, the entire period of operation of the Landsat 2, 4-5, 8, 9 satellites for 1975-2024 is considered, but these materials have not yet been fully analysed.

Figure 4. Sediment input into the Chorokhi River delta in 1987 (left) and 2015 (right)

Visualization and classification of images (Fig. 5) made it possible to approximately assess the processes of some drainage of this delta territory due to the regulation of the river flow and the intensification of its economic development. Thus, over the entire territory of 3,730 hectares, the area of water surface decreased from 303 to 251 hectares, the area of wetlands decreased from 594 to 237 hectares, but the area of gardens and meadows increased noticeably - from 487 to 921 hectares. The area of forests and built-up areas has not changed significantly.

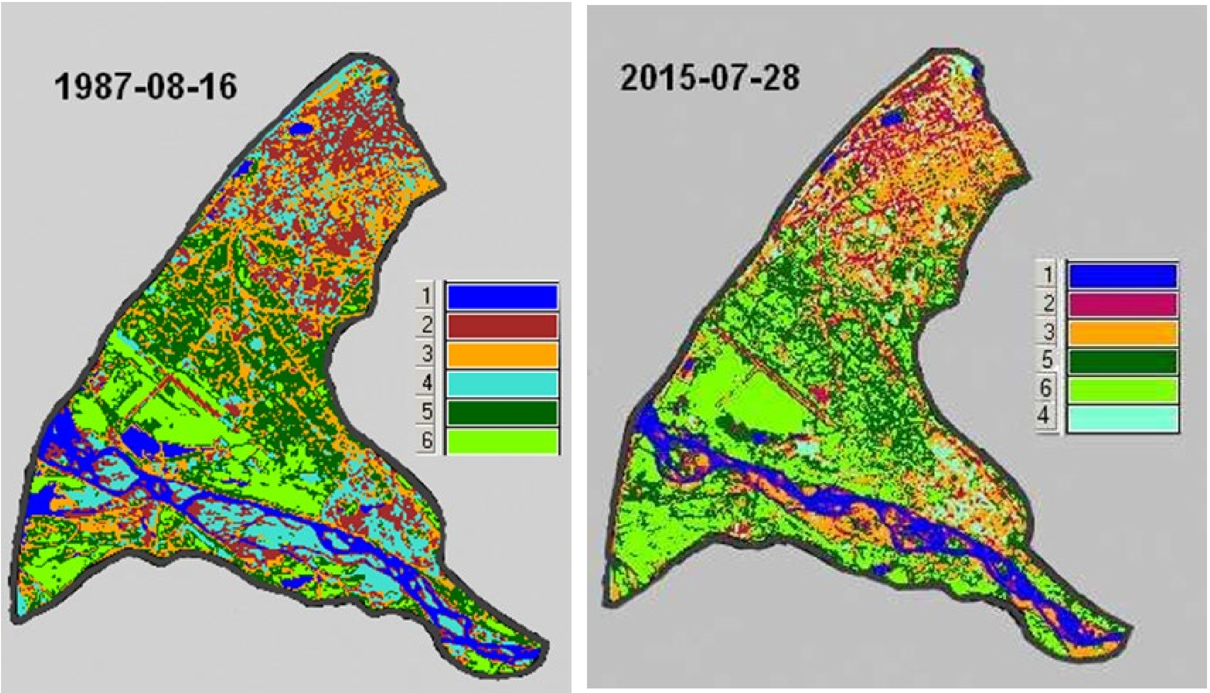

Figure 5. The Chorokhi River delta in Landsat 5 (1987) and Landsat 8 (2015) images and their classification: 1 - water surface, 2 - buildings, 3 - impervious areas, 4 - wetlands, 5 - forests and parks, 6 - meadows and gardens.

To determine changes in the shoreline of the delta, a shapefile of this delta in the Landsat-8 image in 2015 was superimposed on the Landsat-5 image in 1987. The results indicate the retreat of the coastline—that is, coastal erosion— in the river mouth and in the area between the mouth and the city of Batumi. Considering the approximate nature of the values obtained in this way, we note that in the river mouth the coastline shifted to the east over the period 1987-2015 by 120-150 m, and in the area between the mouth of the river and the city of Batumi these values were -60-90 m, respectively. Within the city of Batumi itself, the coastline displacement was mostly less than 1 pixel (30 m) and in a westerly direction. That is, a weak tendency towards sediment accumulation appeared here. This value was clarified using the Planet Earth mapping service (Fig. 6). For this purpose, the function of this service, “change of image over time”, was used, which made it possible to approximately identify the displacement of the coastline towards the sea for the period 2004-2016, amounting to 10-35 m. The same trend of increasing the width of the beach coast in Batumi was confirmed in 2018 and then in 2024.

To determine specific territories where changes occurred, as well as their areas, the “change detection” function of a specialised program was used (Fig. 7). As a result, it was revealed that in the area of the mouth of the Chorokhi River, during the period from 1987 to 2015, The areas that most protruded into the sea, covering an area of 14 hectares, were eroded, while at the same time, part of the sediments formed as a result of erosion of the riverbed accumulated at the mouth. In the area from the river mouth to the city of Batumi, a one-way directional process of bank erosion was noted over an area of 16 hectares. In the area of the city of Batumi itself, sediment accumulation occurred on an area of 20.5 hectares and the coast extended tens of meters into the sea. Sediment accumulation was also noted north of Batumi (in the bay).

Figure 6. Changes in the coastline in the city of Batumi for the period 2004-2018

To ensure the reliability of the data obtained, an attempt was made to analyse images of the Landsat space satellites for the entire period of their operation, that is, from 1976 to 2024. However, the images for the period 1976-1986 were of low quality, so the results obtained will be refined. Nevertheless, we present them in this message. In the city of Batumi for the period 1976-2000 the increase in the beach coast was 45 m over the period 2000-2024 - another 30 m, and in total for 1976-2024 - 75 m. In the middle of the space between the mouth of the Chorokhi River and Batumi, due to erosion, the coastline retreated to the east in 1976-2000 by 75 m, in 2000-2024 - by 50 m, and in total for 1976-2024 - by 125 m. At the same time, at the very mouth of Chorokhi, the processes of erosion and accumulation alternated in years of different water content.

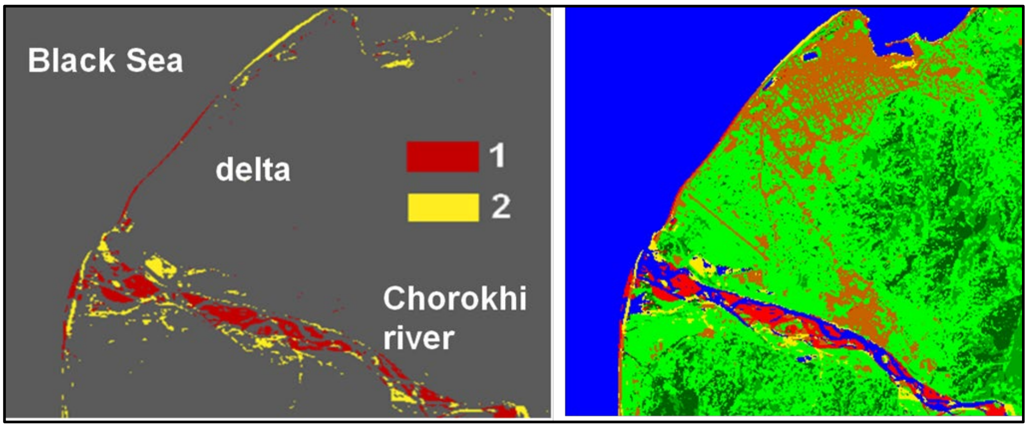

Figure 7. Changes in the coastline in the Chorokhi River delta for the period 1987-2016

Results

Rioni estuaries

The Rioni River is located in Georgia and has a length of 327 km, and a drainage area of 13,400 km^2. It begins in the Caucasus Mountains, and below the city of Kutaisi it flows through the fertile Colchis lowland with a humid subtropical climate (Fig.8) and flows into the Black Sea near the city of Poti. The annual volume of water flow is estimated at 13.37 km^3, including 9.62 km^3 of water flowing along the northern (new) channel, and 3.75 km^3 of water flowing through the southern channel (Jaoshvili, 2002). The flow of the Rioni is regulated by a cascade of small hydroelectric power stations (Lajanuri, Gumati 1 and 2, Rioni Vartsikhe hydroelectric power stations), but due to the small volume of reservoirs, they did not have a significant impact on the river's water flow. Important changes in flow occurred when in 1939 the mouth of the Rioni was artificially diverted north of the city of Poti to protect it from floods, and in 1959 part of the river's flow was returned to the old channel (Fig. 8). The river's water resources are used mainly for energy, water supply and irrigation.

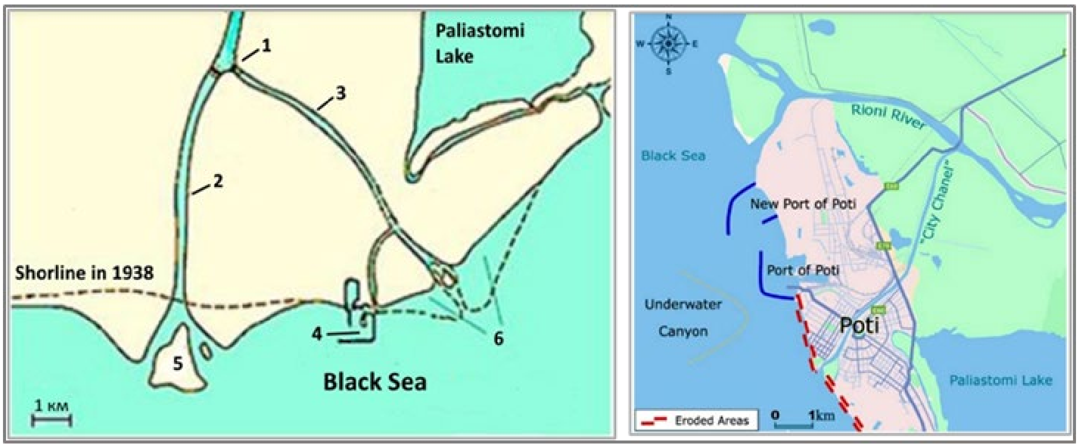

Figure 8. Artificial direction of the Rioni flow along the northern channel - left and changes in processes on the coast in connection with the creation of a new port (Saghinadze et al et., 2024)

The formation of the area between the old and new channels of the Rioni River (Rioni delta) is also significantly influenced by modern changes in the sediment flow of the river (3.54 million tonnes per year) and along-shore sediment flows of the Black Sea. The natural dynamics of sediment in the river were changed due to flow regulation, but after the reservoirs were filled with sediment, their flow began to return to the natural state (Jaoshvili, 2002). The direction of the river flow in 1939 along the northern channel to protect the city of Poti from floods had a dramatic effect on the influx of sediment at the mouth of the Rioni. As a result, the urban area began to be eroded, so part of the river flow was again returned to the old channel. In 1939, the direction of the river flow along the northern channel had a dramatic effect on the influx of sediment at the mouth of the Rioni, protecting the city of Poti from floods. As a result, the urban area began to be eroded, so part of the river flow was again returned to the old channel. And in the northern channel, the bank began to grow. The creation of the delta area here and how the river and sea interact were mostly influenced by the movement of sediment along the shore towards the centre of Colchic Lowland. But with the transfer of the Rioni flow along the northern channel, the growth of the coast here led to a shift in the sediment flow to the north (Fig. 9).

Figure 9. Sediment movement near the coast of Rioni delta (Sentinel-2, 2024-06-02)

And the process of sediment accumulation between the mouths of the Rioni and Khobi rivers has intensified in recent decades in connection with the reconstruction of port facilities here and has led to further growth of the coast. It is this process that we studied using modelling methods and remote sensing.

The remote sensing technique for the case of Rioni was based on a comparison of Landsat 2, 5 and 8 satellite images for the period 1975-2016. To compare images from different years, a shapefile (aoi) was created on the 2016 image. It was superimposed sequentially on images from 1975, 1980, 1987, 2000 and 2009, which made it possible to identify an area of the sea that was gradually replaced by land due to sediment accumulation (Fig. 10). Now such research continues for the period until 2024 using the "change detection" computer technique. The landscapes of the Rioni delta were analysed using "unsupervised classification". The calculation of land and water surface areas within the study area (2943 hectares) showed that the size of the land for the period 1975–2016 increased by 366 hectares (Table 1). That is, the rate of land growth during this period averaged 8.93 hectares per year (according to modelling data, land growth towards the sea was 7-8 m/year). It is important to note that in recent decades the rate of land growth has slowed to 6-7 hectares/year.

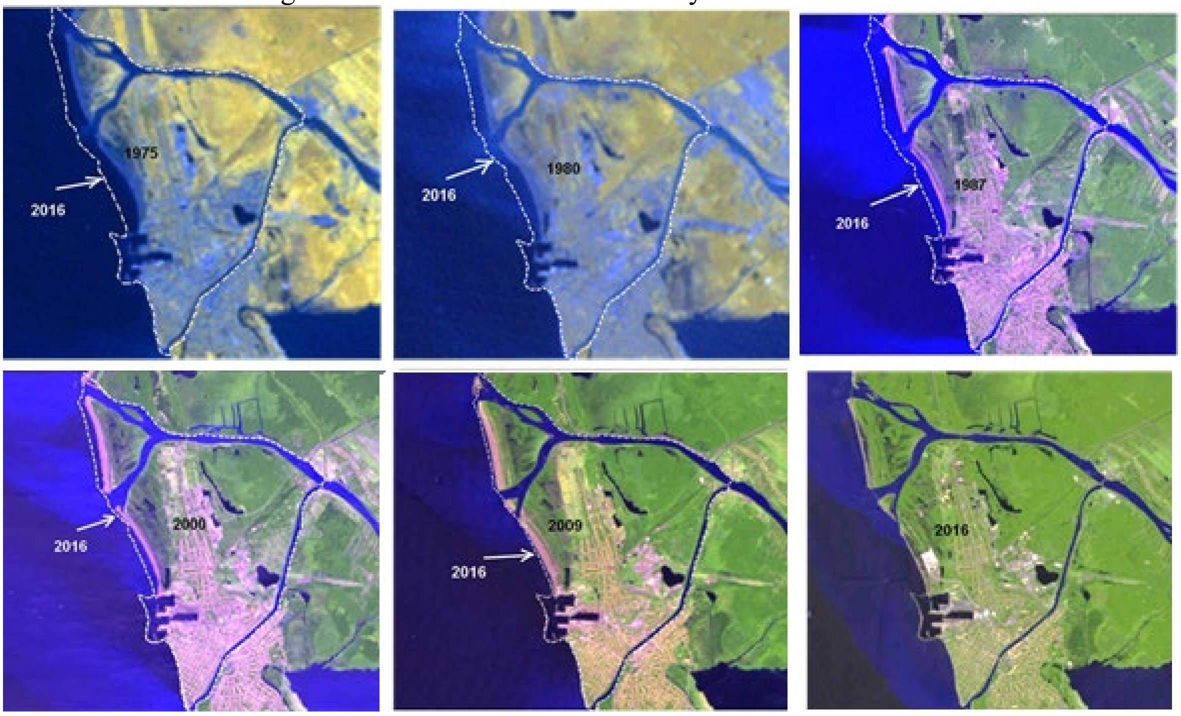

Figure 10. Changes in the delta coastline for 1975-2016

New lands formed in the coast of the delta are mainly a recreational resource. But it is also important to assess changes in land cover throughout the delta, which serves as a resource for agricultural production, environmental protection measures and the development of the city of Poti with all its infrastructure. Considering the low quality of Landsat-2 images, the assessment of changes in the structure of land cover was made only using the Landsat-5 and 8 satellites for the period 1987-2016 (Fig.11).

Table 1. Changes in the structure of land cover of the Rioni delta within the boundaries of the studied territory for the period 1987-2016, ha

Land	Land area, ha		Changes in area, ha
	1987	2016	
Water surface	**566**	**386**	**-180**
Buildings (residential, communal, industrial)	**668**	**737**	**+69**
Landscape gardening	**587**	**632**	**+45**
Forests (including floodplains)	**490**	**682**	**+192**
Wet meadows with shrubs	**399**	**279**	**-120**
Wetlands	**233**	**227**	**-6**
Total	**2943**	**2943**	_

In general, changes in the land cover of deltaic region of the Rioni River are due to the redistribution of river flow into the northern and southern channels, alongshore sediment flows into the sea and, to a lesser extent, regulation of flow by dams and reservoirs. A study of the dynamics of the delta in time and space based on remote sensing data from Landsat satellites showed that for the period from 1975 to 2016. The area of the part of the delta we studied increased by 366 hectares, and the average rate of its increase was 8.93 hectares/year. The protrusion of the delta into the sea occurs in the northern and middle part of this region, in the southern part (the city of Poti) the coastline is now relatively stable with tendency to erosion, and to the south there is coastal erosion. The obtained parameters for the increase in the Rioni delta can be used for forecasting for the coming years, especially in connection with the construction of a new port. The new lands formed in the delta of the Rioni River are mainly a recreational resource. But throughout the delta there is an improvement in the agro-ecological condition of the lands, which serve as a resource for the development of the region.

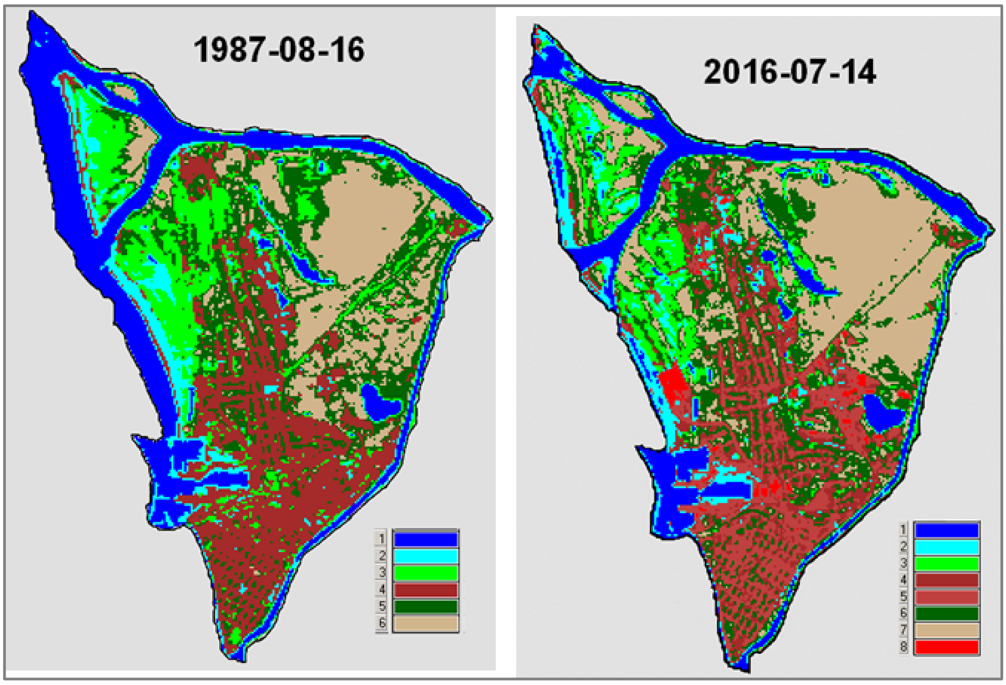

Figure 11. Changes in the structure of land cover in the Rioni River delta. (In both legends: 1 - water surface, 2 - wetlands, 3 - wet meadows. In the legend for the 1987 image: 4 - buildings, 5 - gardens and parks, 6 - forests. In the legend for the 2016 image.: 4, 5 and 8 – individual, communal and industrial buildings, 6 – landscape gardening, 7 – forests

Delta of the Kizilirmak River

River deltas on the southern coast of the Black Sea (within Turkey) are formed both under flow regulation by dams and reservoirs and under the influence of powerful waves and latitudinal longshore currents. The largest river here is the Kizilirmak, whose delta is of international importance as a wetland for waterfowl habitat. Farmland, including irrigated fields and fruit plantations, occupies the flat areas. The length of the river is 1355 km, and the drainage area is 78646 km² (Jaoshvili, 2002). It originates in the mountains in inland Anatolia; in its lower reaches, it cuts into a plateau to a depth of about 600 m and flows into the sea on a swampy plain near the city of Bafra. The river mouth has formed an underwater sandbar (Jaoshvili, 2002), which influences the modern processes of coastal erosion.

The modern delta, which is a plain dotted with a network of channels and canals, was formed over a period of about 10,000 years (Erdoğan, 1970). It lies at altitudes of 0-15 m and ends in a swampy lowland with lagoons, bordered by dunes. Today, most of the delta is used for agricultural production, including rice growing. And behind the barrier of sand dunes, the configuration of which was determined by the interaction of the influx of river sediments and alongshore sea currents, lagoons were formed that have unique environmental value (Erdoğan, 1970).

Our research includes an analytical review of published materials on the problem of degradation of delta wetlands, as well as an analysis of temporal and spatial changes in the Kizilirmak River delta based on Landsat satellite images for 1980–2016 and then until 2024. Big changes in the land cover of the delta happen because of 1) erosion and buildup of materials on the sea coast (Algan et al., 2000; Hay, 1994); 2) less river water and sediment flowing into the delta, which harms the wetland areas; 3) different ways the land is used (like for irrigation, farming, grazing, and protecting wetlands). Erosion-accumulation processes on the sea coast depend on the wave activity of the sea and along-shore currents, on the one hand, and the accumulation of river sediments, on the other. In the Kizilirmak delta, the amount of river sediment coming in dropped significantly after the Altynkaya and Derbent reservoirs were built nearby (Fig. 12). And the activity in the sea (winds, waves, currents) remained almost the same. Therefore, we compared the delta coastline in 2010 and 1980, that is, over 3 decades, as well as in 2014 (Fig. 13).

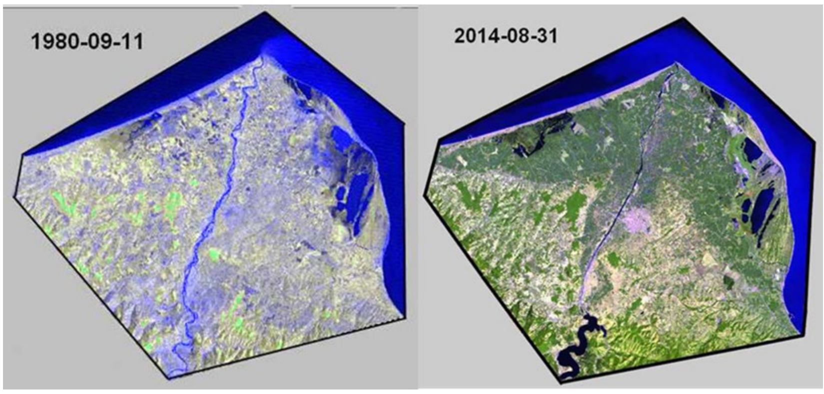

Figure 12. The Kizilirmak River delta before and after the construction of reservoirs in the lower reaches and straightening of the riverbed (Landsat images 2 and 8)

And the activity of the sea (winds, waves, currents) remained almost the same (Fig. 13). Therefore, we compared the delta coastline in 2010 and 1980, that is, over 3 decades, as well as in 2014 (Fig. 13). An approximate graphical assessment of changes in the coastline for the period 1980-2010. showed that the western coast (Fig. 13, site 4) has changed little. Erosion here appeared at a distance of 0-60 m, that is, within one pixel on the raster image. Erosion was more severe to the east of the river mouth (Fig. 13, site 1), spreading here over a distance from 60-120 m to 360-420 m (6-7 pixels). At the same time, on the eastern coast, areas of sediment accumulation were identified, where the sea retreated by 120-240 m (site 2) and from 120-180 to 240-360 m (Fig. 13, site 3). We compared these results with data from (Ozturk et al., 2015), according to which coastal erosion east of the river mouth amounted to 655 m. Moreover, special spurs (Fig. 14) weaken erosion processes here, but do not prevent them completely.

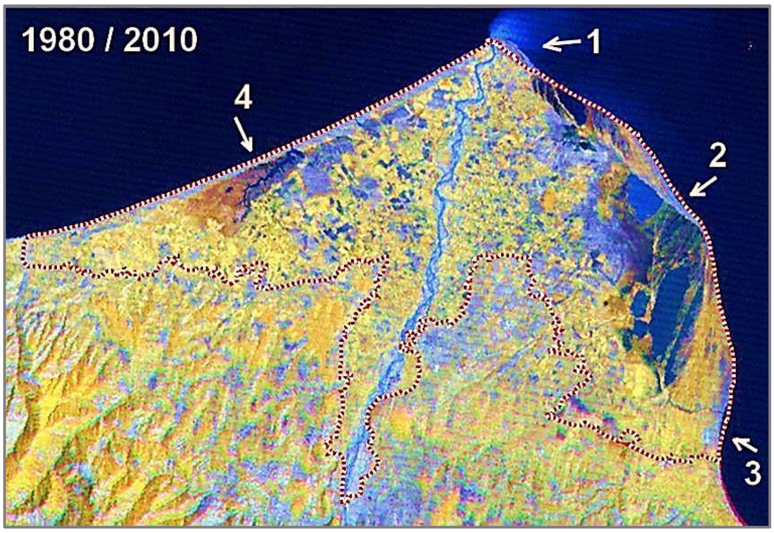

Figure 13. Changes in the delta coastline for the period 1980-2010 (1, 4 – erosion; 2, 3 - accumulation)

Conclusions: a) Reduced water and sediment flow into the Kizilirmak River delta and economic activities in it have caused noticeable changes in land cover; b) The interaction of land and sea in conditions of a decrease in the influx of river sediments caused the activation of erosion-accumulation processes in the delta. Wave activity and alongshore currents caused coastal erosion mainly east of the river mouth and local accumulation of sediment on the east coast; c) The water surface of lakes and estuaries in the delta has decreased by 1-2 thousand hectares over a 30-year period due to the transformation of water bodies into wetlands. Quantitative indicators of the decrease in wetlands in the Kizilirmak Teka delta need to be clarified by further monitoring.

Dnieper delta

The Dnieper River flows through the territory of three countries - Ukraine, Belarus and Russia. The total area of the basin is 504 thousand km^2, of which: 20% is in the Russian Federation, 23% - in the Republic of Belarus, and 57% (296,317 thousand km^2) - within Ukraine. The total length of the Dnieper is 2,201 km, within Ukraine – 1,121 km (Vishnevsky, 2011). Before the war between the Russian Federation and Ukraine, more than 20 million people lived in the Ukrainian part of the Dnieper basin, but now this number has significantly decreased. The plowed area of the basin is 69% of its total area, that is, it is quite high.

Figure 14. Protection of the banks from erosion east of the mouth of the Kizilirmak River with special spurs created in 1999-2010 (Sentinel-2)

The degree of regulation of the flow of the Dnipro is very high. The river is regulated by a cascade of Dnieper reservoirs – Kyiv (previously – Kiev), Kaniv, Kremenchuk, Kamianske (previously - Dniprodzerzhynsk), Dnipro, Kakhovka (destroyed on 6 June 2023). Regulation of the Dnieper flow began back in 1932 with the construction of the Dnieper hydroelectric power station, but this did not noticeably affect the landscapes of the river delta. More significant changes in the water regime of the delta and its ecosystems began in 1956-1957, when the large Kakhovka reservoir, created for irrigation, energy, water supply and water transport, was filled. And then, until 1975, a whole cascade of 6 reservoirs was created with a total volume of 43.8 km^3, a useful volume of 18.5 km^3 and an area of about 7000 km^2. During the same period, large canals were built that drain water from the Dnieper (North Crimean, Kakhovsky, Dnieper-Donbass, Dnieper-Ingulets, Dnieper – Kryvy Rig), and the consumption of Dnieper water for municipal, industrial and agricultural water supply increased. The total area of the water in the reservoirs of the cascade is about 7,000 km^2 with a total water volume of 43.71 km^3 and useful volume of 18.5 km^3. There are some large canals that divert water from the Dnieper River: The Dnipro-Donbas canal, the Kakhovsky main canal, the North-Crimean canal, the Dnipro-Kryvyi Rih canal and the Dnipro-Ingulets canal.

Figure 15. Deltas of the north-western coast of the Black Sea (1 – Dnieper, 2 – Dniester, 3 – Danube) Results

The average long-term rate of the natural flow of the Dnieper previously increased downstream from 593 m^3/s at the "Nedanchichi" hydropost (the entry point for the territory of Ukraine) to 1,690 m^3/s at the mouth of the Dnieper. Now the flow rates are fully regulated by the reservoirs and in the last decade, which was low-water, amounted to 500-600 m^3/s. Average long-term natural volume of runoff in the estuary was 53.3 km^3, and now it has decreased by approximately 11 km^3, that is, it has become 20% less than the natural one. Inflow of sediments during this period also decreased from 2.6 to 0.6-0.8 million t/year, as they now accumulate mainly in the upper (Kyiv) reservoir. It is important to note that at the top of all reservoirs of the cascade, except for the deep and narrow Dnieper one, peculiar delta-like hydromorphic landscapes began to form due to the accumulation of solid runoff, organic sediments and the development of wetland vegetation and floodplain forests. However, this process is still at the initial stage due to the small amount of solid runoff from the Dnieper in comparison, for example, with the formation of a new delta in the Kapchagai Reservoir on the Ili River in Kazakhstan, where the solid runoff exceeds 11 million tons per year (Starodubtsev, 2007c). The most active process of such delta-like landscapes formation takes place in the Kyiv Reservoir, the first in the cascade, which accumulates almost the entire solid runoff of the Dnieper - on an area of about 20000 ha. It continues in the large Kremenchutsk and Kakhovka reservoirs, and only fragmentarily in the small Kaniv and Kamianske reservoirs. These new landscapes have a very large significance for biodiversity, nature protection, recreation, hunting, sport, etc.

Figure 16. Dnieper Delta before flooding (2023-06-03)

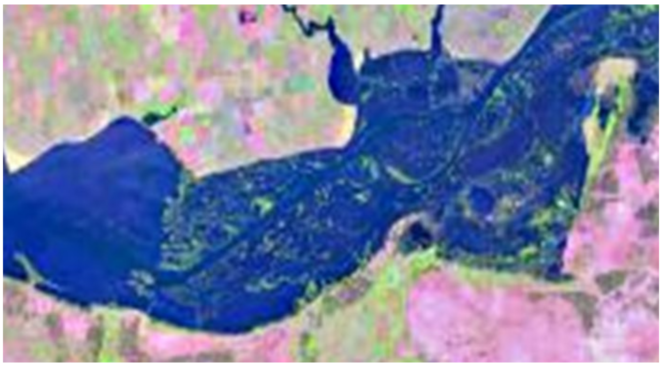

Figure 17. The Dnieper Delta is flooded on the 4th day (2023-06-09)

The Dnieper Delta is formed in a narrow long canyon and ends with the Dnieper-Bug estuary on the Black Sea coast. It begins near the village of Oleshki, stretches for more than 42 km and ends in the Dnipro-Buzka estuary. The total area of the delta is estimated at approximately 350 square kilometers. This area is very rich in biodiversity, so it is included in the list of wetlands of international importance protected by the Ramsar Convention. Before the construction of a cascade of dams and reservoirs, the delta gradually grew in the estuary towards the Black Sea, representing a collection of numerous channels, lakes, islands, swamps overgrown with reeds, and weakly expressed ramparts with shrub and tree vegetation. However, after a flow regulation the influx of water and sediment into the delta has decreased, water quality has deteriorated, and powerful flood spills, which now occur only in record-high water years, have practically ceased. The restructuring of landscapes began, accumulative processes and the protrusion of the delta into the Dnieper-Bug estuary noticeably weakened. Stagnation processes, eutrophication of lakes and streams increased. The massive construction of country houses on the levees along the large straits greatly contributed to the processes of eutrophication.

Our research is carried out in the contour from the Antonovsky automobile bridge across the Dnieper River to the estuary on an area of 37.4 thousand hectares. Schematic zoning of the delta based on ground-based route studies and analysis of Landsat satellite images for the period 1975-2013. made it possible to identify areas with different intensity of overgrowing of water bodies with hydrophylic and hydrophytic vegetation, “blooming” of water, and areas of economic use. However, in recent years, there has been a noticeable lack of water on the Dnieper and a decrease in water flows from the

Kakhovka reservoir to the delta, reaching 300-500 m^3/s in certain periods. This led to an intensification of the processes of overgrowing the delta with coastal aquatic vegetation and a significant increase in the areas of floodplains with trees and shrubs. The area of settlements, dachas and anthropogenically modified territories is also noticeably increasing, reaching more than 4 thousand hectares in 2015. The “blooming” of water in the estuaries and lakes of the delta has also increased. Such trends persisted until 2021, after which changes were caused by the war in Ukraine.

Figure 18. Dnieper Delta on the 12th day after flooding with destroyed vegetation and covered

As the delta changes, the likelihood of fires increases, destroying all unique biota. Thus, in the spring of 2016, the consequences of large fires that occurred in the autumn-winter period were revealed. The area of the fires amounted to more than 5 thousand hectares, of which on an area of 2.8 thousand hectares the vegetation was completely burned out, including trees and shrubs, and on an area of 2.2 thousand hectares - partially. Since 2022, with the outbreak of the war, the area of fires in the territories adjacent to the delta has sharply increased due to shelling and bombing.

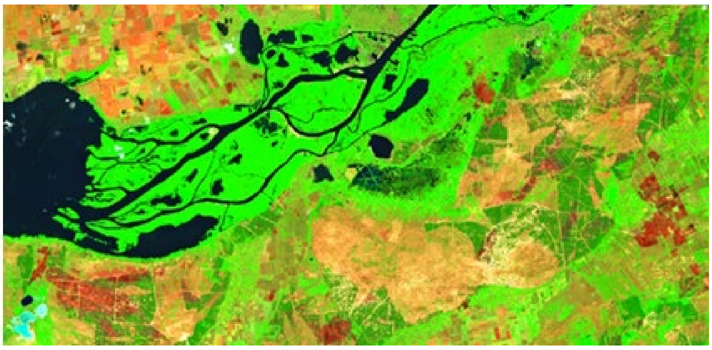

Figure 19. Gradual restoration of delta wetlands after 3 months with traces of fires from artillery

Profound changes in the Dnieper delta occurred after the destruction of the dam and power station of the Kakhovka reservoir on June 6, 2023. These changes are shown at these satellite images (Fig16-19):

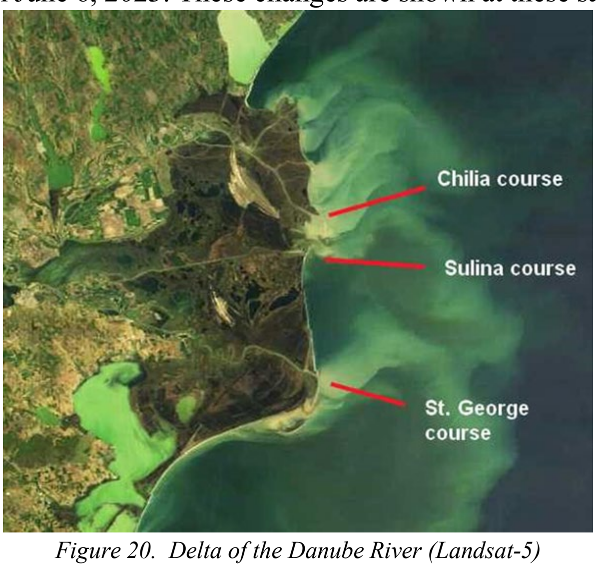

Figure 20. Delta of the Danube River (Landsat-5)

Danube Delta.

The Danube River is the second largest river in Europe with a catchment area of 817,000 km². The Danube basin covers the territory of 18 countries, the largest parts of the basin are in Romania (28.9% of the area), Hungary - 11.7%, Austria - 10.3%, Serbia - 10.3%. The length of the river is 2857 km. The average annual flow of the Danube is, according to various estimates, from 203 to 210 billion m3 (57% of the annual flow of all rivers flowing into the Black Sea), and the average flow rate is 6500 m^3/s. Sediment runoff in its natural state was approximately 56-83 million tons every year, but under the influence of economic activity (water regulation and water use) it has significantly decreased (Fig. 20).

Figure 21. Our field routs in the Ukrainian part of the Danube delta

The source of the Danube is in the mountains in Germany, and then it flows along the Middle Danube lowland to the "Iron Gate" gorge in the south of the Carpathians and on to the Black Sea. The importance of the Danube basin for the European economy is extremely high. When it flows into the Black Sea, the Danube forms a giant delta with an area of 5640 km². The top of the delta is near Cape Izmailsky Chatal, 80 km from the mouth. Here, the main channel of the Danube first branches into the Kiliy estuary, which flows into the sea on the territory of Ukraine, and the Tulchyn estuary, which 17 km downstream divides into the Georgievske and Sulinske estuaries, which flow into the Black Sea in Romania. Floodplains, with a multitude of canals, lakes, and marshes, primarily cover the area. The delta was quickly pushed into the sea by a large amount of sediment before the flow of the Danube was intensively regulated by reservoirs, especially on its numerous tributaries. However, due to hydraulic construction in the basin and the ever-increasing use of Danube water in its economy, the total flow of water and especially sediment is significantly reduced. Thus, the delta's advance into the sea has slowed, and the processes of accumulation and erosion of the delta's sea edge are clear. A cross-border biosphere reserve, "Danube Delta," has been created in the Danube Delta and is included in the World Network of Biosphere Reserves. It includes the 580,000 ha Danube Delta Biosphere Reserve in Romania and the Danube Biosphere Reserve in Ukraine.

For now, our research is focused mainly on the Ukrainian part of the delta, where the process of the delta's extension into the sea continues), which, however, becomes more complicated from year to year depending on the water level of the year and the peculiarities of the influence of sea currents and waves. In general, our preliminary calculations (Starodubtsev, 2013)indicate that in the Danube delta, the area of the water surface decreases by an average of 500 ha each year due to the overgrowth of lakes and channels with air-water and water vegetation, economic development of land, and partly due to the increase in the area of the Chiliya part of the delta, which we explored by land routes (Fig.21).

The state of wetlands and their gradual agricultural development, especially in the northwestern part, significantly affects the state of wetlands. As for the sea edge of the Danube delta, it changes depending on the inflow of sediments and the influence of sea currents and waves. In the north-eastern and central parts of the delta, the delta is moving slowly into the sea, that is, mineral and organic sediments are accumulating and the area of the delta is increasing, especially its Ukrainian part. And in the northeastern part of the delta, erosion and erosion of the shore prevail.

A very serious problem for the biodiversity of the huge delta is the frequent and large-scale fires that occur due to natural phenomena, but to a greater extent due to the irresponsible (and sometimes intentional) actions of poachers and even the personnel of the biosphere reserve (Fig.22).

Such fires cause great damage both to the unique colonies of migratory birds and to all species of the delta's animal world. Fires cause irreparable damage to floodplain forests and shrubs, which take an immeasurably longer time (years) to regenerate compared to grassy vegetation.

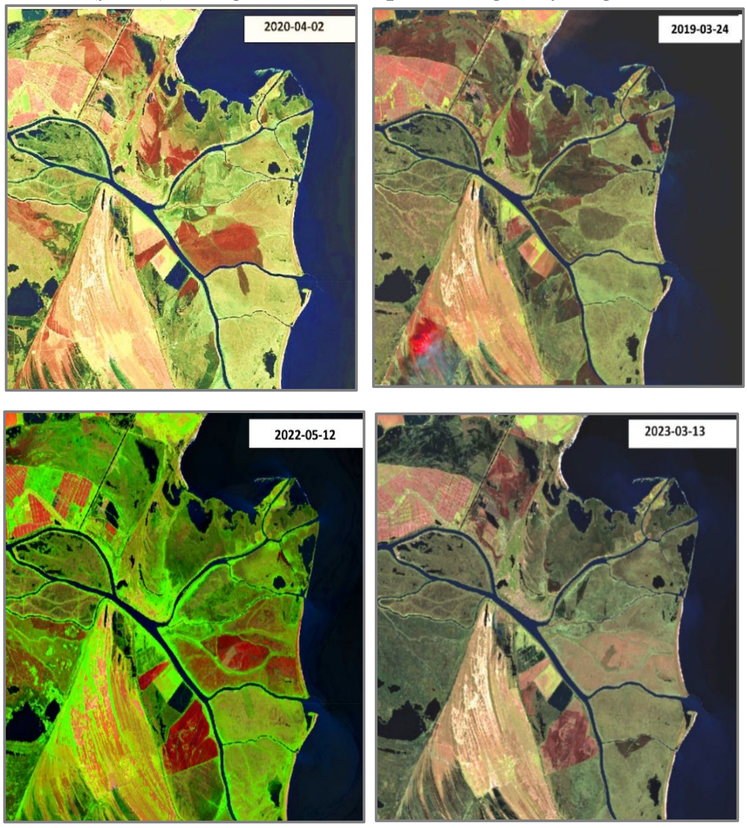

Figure 22. Fires in the northeastern part of the Danube Delta (Sentined-2 satellite images)

Conclusion

The way river flow regulation affects river deltas, and the local economy varies based on the climate, landforms, how the flow is managed, and other natural characteristics of the delta area. In the Black Sea basin, it's easy to see that changes in the deltas are mainly influenced by how they interact with the sea. In the Black Sea basin, changes in the deltas can be clearly traced, primarily depending on how they interact with the sea. On the Caucasian coast, deltas experience the influence of alongshore flows of sea water and sediments from the north, leading to coastal erosion at river mouths and sediment accumulation north of these mouths. Therefore, the erosion of the recreational zone (beach) in Batumi remains a topic of discussion now. Erosion processes are also taking place in the southern part of Poti city, but sediments are actively accumulating in the middle and northern parts of the coast. And their accumulation can create problems for the infrastructure under construction, around the new Port.

The deltas of the rivers on the Turkish coast, particularly the Kizilirmak River, are strongly influenced by the alongshore currents in the eastern direction. Their western shores have already formed high dune formations that slow down erosion processes. But in the mouths of rivers and on the eastern shores, turbulent flows intensively erode the shores, so special protective structures are already being built here to protect against erosion, although they do not fully protect against it. It is important to note that the circulating water flows along the eastern shore form alternating areas of erosion and sediment accumulation.

And this affects personally valuable extensive wetlands and the infrastructure of the coast occupied by recreational organisations and settlements.

Regulation of the flow of the rivers along the Caucasian and Turkish coasts in general optimises the water regime of the deltas and promotes their effective use in agriculture, horticulture, and recreation. However, we need to take measures to protect the valuable Ramsar wetlands.

Long estuaries form the deltas of the northern coast of the sea (Dnieper, Dniester), which do not interact with the sea. Therefore, their landscapes have sharply slowed their advance toward the sea and are experiencing stagnant phenomena. To optimise the water regime of ecosystems and support fisheries, they need spring flushing releases from reservoirs. They currently face the devastating effects of war.

Both the river and the sea influence the Danube Delta. On a huge area of wetlands, there is a tendency to decrease the area under water (lakes, channels) and increase under vegetation at a rate of about 500 hectares per hour. The northwestern part of the delta is being developed for agriculture. On the seacoast of the delta, mineral and organic deposits mainly accumulate in the northern (Ukrainian) and middle parts, but erosion occurs in the southern part.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

V.S. made the biggest contribution, conceived of the presented idea, and took the lead in writing the manuscript. M. K. characterized Chorokhi and Rioni deltas. M. L. characterized Dnieper and Danube deltas. V. B. performed the cartographic part. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

ORCID iD

Vladimir Starodubtsev https://orcid.org/0000-0002-7053-2032
Manoni Kodua https://orcid.org/0000-0002-3186-9062
Maryna Ladyka https://orcid.org/0000-0002-5164-7117
Vyacheslav Bogdanets https://orcid.org/0000-0003-0051-1778

Reference

Bayram, A., & Kenanoglu, M. (2016). Variation of total suspended solids versus turbidity and Secchi disk depth in the Borçka Dam Reservoir, Çoruh River Basin. *Lake Reserv Manag, Vol 32*, 209-221.

Berkun, M., Aras E., & Akdemir, U. O. (2015). Water runoff, sediment transport and related impacts in the southeastern Black Sea rivers. *Environmental Engineering and Management Journal, 14(4)*, 781-791.

Erdoğan, A. (1970). *Geomorphology of the Kızılırmak Valley: Between Bafra Burnu and Delice Junction*. Ankara: Ankara Üniversitesi Basımevi.

Eruz, C., Kose, E., Guneroglu, A., Basar, E., Sivri, N., Feyzioglu, A. M., & Toraman, C. (2005). Suspended Solids Dynamics in the Eastern Black Sea rivers (in Turkish). *Turk Sucul Yasam Dergisi, 4*, 235-239.

Gagoshidze, Sh,, Kodua, M., Saghinadze, I., & Kadaria, I. (2017). *River hydro construction and geomorphological processes in the Black Sea coast of Georgia*. Tbilisi: 1st ed. Technical University.

Glenn, E.P., Lee C., Felger, R., & Zengel, S. (1966). Effect of water management on the wetlands of the Colorado River delta. *Conservation Biology 10(4),* 1175-1186.

Hay, B. J. (1994). Sediment and water discharge rates of Turkish Black Sea rivers before and after hydropower dam construction. *Environmental Geology, 23*, 276-283.

Jaoshvili, Sh. (1986). *Rivers of the Black Sea* (In Russian). Tbilisi: Sabtchota Sakartvelo.

Jaoshvili, Sh. (2002). *The rivers of the Black Sea*. Technical reports 71. Kopenhagen: European Environment Agency, 1-58.

Kiknadze, A. G. (1976). Dynamic systems and sediment budget in streams along the Black Sea coast of Georgia. In *Dynamics of seacoasts* (In Russian) (pp. 68–70). Tbilisi: Metsniereba.

Klaphake, A., & Scheumann, W. (2011). Coruh River Basin: Hydropower development and transboundary cooperation. In Springer eBooks (pp. 251–261). https://doi.org/10.1007/978-3-642-19636-2_14.

Makatsaria, A. (1973). Causes and possible measures to eliminate coastal erosion near the city of Poti. *Works of Geographer Communities of Georgia*. Tbilisi: Metsniereba.

Mikhailova, M, V. (2009). Water and sediment runoff at the mouths of rivers flowing into the Black Sea. *Environmental Research. Engineering and Management, Vol. 48*, 5-10.

Mikhailova, M. V., & Jaoshvili, Sh. V. (1998). Hydrology-morphological processes in the mouth area of the Rioni and their anthropogenic change (In Russian). *Water Resources, Vol. 25*, 152-160.

Ozturk, D., Beyazit, I., & Kilic, F. (2015). Spatiotemporal Analysis of Shoreline Changes of the Kizilirmak Delta. *Journal of Coastal Research 31(6),* 1389-1402. doi: https://doi.org/10.2112/JCOASTRES-D-14-00159.1

Saghinadze, I. (2013). Calculation of the coastal currents of the Black Sea in the area of Poti. *Journal of Georgian Engineering News, 2(66),* 101-104.

Saghinadze, I., & Kodua, M. (2019). A Mathematical Model of Sediment Transport of the Poti Coastal Zone. *International Journal of Engineering Research and Technology, 12(12)*, 3032-3037.

Saghinadze, I., Kodua, M., & Pkhakadze, M. (2024). The Influence of the New Breakwater of Poti Port on Litho-dynamics of the Coastline. *International Journal of Engineering Trends and Technology 72(5),* 227-231.

Sezer, U. (2009). Coruh river development plan. *International Workshop on Transboundary Water Resources Management*. Tbilisi: KS (DSI).

Starodubtsev V. M. (2013). Changes in the Danube Delta According to Remote Sensing Data by Landsat Satellite. *Arid Ecosystems, 4(3)*, 258-262.

Starodubtsev V, M. (2014). Flow regulation impact on land cover changes in river deltas of the Black Sea basin. Retrieved from http://www.sworld.com.ua/index.php/ru/conference/the-content-of-conferences/archives-of-individual-conferences/june-20

Starodubtsev V, M., & Petrenko, L. R. (2005). *Soil desertification in the river deltas (Part 1)*. Kyiv: Nora-Druk.

Starodubtsev V, M., & Truskavetsky S, R. (2011). Desertification processes in the Ili River delta under anthropogenic pressure. *Water Resources, 38,* 253-256.

Starodubtsev, V. M. (2007). Degradation Processes in Deltas of the Rivers with Flow Regulation. *Basin Water Management. Intern. Congress on River Basin Management,* 828-843. Retrieved from http://www2.dsi.gov.tr/english/congress2007/chapter2/66.pdf

Starodubtsev, V. M. (2017). Changes in land cover in the Rioni River delta. *Scientific World, 49*, 98-108. Retrieved from http://www.sworld.education/ntsw/49-2.pdf

Starodubtsev, V. M., & Basarab R, M. (2017). Changes in the Chorokhi River delta under the influence of economic activity. *Scientific works of SWorld, 2(48)*, 106-115.

Starodubtsev, V. M., & Rudchenko L, M. (2017a). Changes in land cover of the Kizilirmak River delta. *SWorld Journal*. Retrieved from http://wwww.sworld.education/index.php/ru/geography-ua217/physical-economic-and-social-geography-ua217/29304-ua217-047.

Starodubtsev, V. M., & Rudchenko, L. M. (2017b). Changes in land cover of the Yeshilirmak river delta. Bioresources and environmental management. *NUBiP of Ukraine, 9(3-4),* 8. Retrieved from http://journals.nubip.edu.ua/index.php/Bio/article/view/8986/8262

Starodubtsev, V. M., & Struk, V. (2013). *Danube delta: view from space*. Kherson: Oldi plus.

Tsereteli, E., Gobejishvili, R., Bolashvili, N., Geladze, V., & Gaprindashvili, G. (2011). Crisis intensification of Geoecological Situation of The Caucasus Black Sea Coast and The Strategy of Risk Reduction. *Procedia - Social and Behavioral Sciences, 19,* 709-715. https://doi.org/10.1016/j.sbspro.2011.05.189