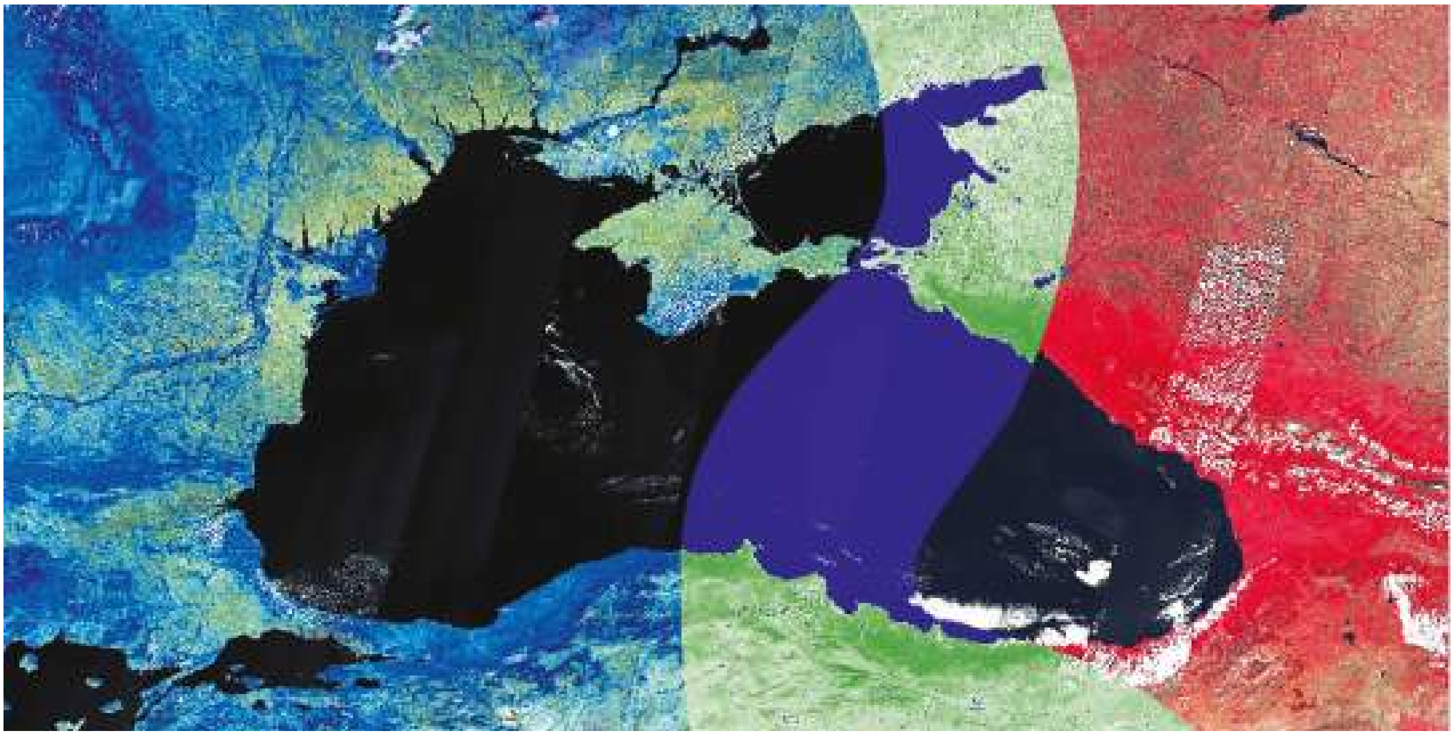
Copernicus assisted environmental monitoring across the Black Sea Basin – PONTOS



Report on Dynamics of Coastal Line Changes

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PONTOS-GE (Georgia)

The entire coastline of Georgia & Downstream part of Rioni river

Tbilisi, 2022

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List of abbreviations

S2	Multispectral satellite
L5	Multispectral satellite
L8	Multispectral satellite
Band	Spectral Channel
NIR	Near-Infrared Spectral Channel
GREEN	Green Spectral Channel
NDWI	Normalized Difference Water Index
DSAS	Digital Shoreline Analysis System
SCE	The greatest distance between all shorelines (m)
NSM	Distance between the oldest and the most recent shorelines (m)
EPR	Distance of Net Shoreline Movement divided by the time elapsed between the oldest and the latest shorelines (in m/y)
WLR	Shoreline Change Rate (m/y)

Foreword

The coast is a special natural environment not only in the view of cultural heritage but also resource distribution which can be evaluated in terms of economic assets. The latter is a dynamic environment that is subject to continuous and constant transformation. Current erosion-deposition events in the coastal zones are affected by a combination of different factors. Changes in the coastal zones are determined by geological, geomorphological, hydrodynamic, biological, climatic and anthropogenic factors (Sytnik et al 2018). Coastal environment where a large share of the world population lives, “40% of the people on the planet lives within 100 km of a coastal zone” (Nicholls et al., 2007), is highly vulnerable to climate change and increasing urbanization. Therefore, the availability of modern information about its condition is of great interest (Zollini et al. 2019).

It should be noted that there is no specific definition of what constitutes a “coastal zone”. It is difficult to place precise boundaries around it, both by land and by sea. According to the general definition, the coastal zone is “the part of the land affected by its proximity to the sea, and that part of the sea affected by its proximity to the land as the extent to which man’s land-based activities have a measurable influence on water chemistry and marine ecology” (United States Commission on Marine Science, Engineering, and Resources, 1969).

In geomorphology, terms with different content are used – “coast” and “coastal zone”. From the geomorphological point of view, the coast is a relatively narrow strip of land adjacent to the coastline, the terrain (relief) of which was created in the recent geological past (Pleistocene, Holocene) as a result of joint activities of various morphogenetic factors. From a general geographical point of view, the coast includes relatively larger land adjacent to the sea, functionally connected to it, with settlements, agricultural fields and infrastructural facilities of various purposes. In such case, the coastal zone can extend from several kilometers to tens of kilometers from the sea. As for the coastal zone, it includes a narrow strip of immediate interaction between the sea and the land. The coastal zone includes only the entire upper level, inland area of the sea aquatory immediately adjacent to the coastline and the coastal land under the influence of tidal waves during the strongest storms. The following geomorphological elements are included in the coastal zone: underwater slope, shore and beach. The boundaries of the coastal zone are determined by considering the range of wave crashing - one of the most characteristic hydrodynamic processes developed within it. The upper level (inland) border of the coastal zone coincides with the line indicating the maximum spread of water flow by wave crashing in the depth of the land. The lower level (outland) boundary passes along the edge of the lower part of the underwater slope - at the depth from which the strongest waves begin to touch the seabed and are deformed. The lower border of the coastal zone of Georgia extends at the depth of 15-20 m and is 100-3500 m away from separate sections of the coastline. Accordingly, the width of the coastal zone of Georgia (the shore and the underwater slope) varies between boundaries of 350-3700 m. (Janelidze 2015, Kiknadze, Janelidze 2000).

Coastal zones are relatively fragile ecosystems and disorderly urbanization, infrastructure development as well as also inconsistent industrial, tourist, and agricultural activities can result in rapid degradation of coastal habitats and resources (Clark 1974).

The most characteristic feature of the coastal zone is its shoreline, the boundary between land and water surface (Clark 1974). The shoreline is a conditional understanding based on ratio of the average multi-year state of the water body level. Coastline morphology is influenced by both natural events and anthropogenic impacts (Clark 1974).

Out of natural phenomena, following should be singled out: tides, sea currents, waves, storms, sea level rise and extreme weather (Tabuz 2015). As for anthropogenic impacts, the following are important: urbanization, tourism, coastal structures, dredging, construction of dams, uncontrolled deforestation along rivers (Mishra et al 2019).

Over time, the location of the shoreline constantly varies due to various factors that change the shape of the beach. The latter can lead to enormous economic problems. Coastal erosion has always existed and over the centuries has contributed to the formation of coastal zones through a delicate ecological balance between river regulation and sea level rise. The increase of anthropogenic activity along the coast disturbed the balance and, accordingly, increased the dynamics of depositional-erosive events. Today, shoreline erosion is one of the most growing environmental problems and therefore it is important to determine the dynamics of shoreline change (Rijn 2011).

Constant observation and monitoring are a necessary condition for sustainable development of the shoreline and its surrounding area. The use of modern technologies, such as aero-topographic observation, remote sensing methods and geo-information systems, are important tools in the view of accuracy of observation, monitoring and evaluation, as well as less financial costs (Giannini et al 2011).

Description of the study area

The study area of the PONTOS project in Georgia is the shoreline of the Black Sea within Georgia, which is 9% of the total length of the Black Sea coast (*Fig. 1*). It stretches over 315 km and has an area of 159 km^2 (a 500 m strip along the 315 km shoreline).

The Black Sea is one of the most important natural formations in terms of the country's general geographical location, resource potential, recreational area, and also the main artery of foreign relations. The study area represents the western border of Georgia, which includes four administrative-territorial regions: Adjara, Guria, Samegrelo-Zemo Svaneti, Abkhazia and is connected to five large hydrological basins: Chorokhi-Adjaristskali, Rioni, Enguri, Kodori and Bzipi.

Fig 1. Study area

A brief overview of the development of the coastal zone of Georgia

In the recent geological past, especially after the Mid-Pleistocene, the Black Sea's level fluctuation regime, coastal aquatorial contours, water chemical composition and biota underwent drastic changes from time to time, which was caused by the periodic interruption-renewal of its bilateral interaction with the Mediterranean Sea. Interruption-renewal of the bilateral interaction between these seas was caused by the glacio-eustatic fluctuation mode of the world ocean level, which was caused by the sharp changes in the global climate during the Pleistocene era.

As a result of the deep glacioeustatic regression developed in the world ocean during the Pleistocene last, late Würm glaciation, the Black Sea basin was covered by New Euxine Lake. The level of the New Euxine Lake was several tens of meters below the modern sea level, and its contour was inside the modern contour of the Black Sea.

According to one part of researchers, the minimal level of the New Euxine Lake (which according to radiocarbon dating occurred 16-18 thousand years ago) was 90-110 meters lower than the modern level of the Black Sea. At that time, the New Euxine Lake was isolated from the Mediterranean Sea and represented a low-salt, almost fresh water body. According to the other group of researchers, the New Euxine Lake was a semi-closed brackish basin, and a river flowed from it through the Bosporus Strait into the Sea of Marmara. The minimal level of the lake was 40-60 m lower than the modern level of the Black Sea.

At the end of the Pleistocene, about 15-16 thousand years ago, as a result of the strong climate warming, which led to the intense degradation of the Würm glaciation, the regression of the world ocean was changed by the so-called Flandrian Transgression. The Flandrian Transgression reached its maximum development at the moment of complete degradation of the Würm glaciation - about 6000 thousand years ago. At this time, the mean ocean level rose to its current level, and since then it has experienced only a slight oscillating fluctuation. From this moment, the development of the modern coastal zones of the ocean and connected seas began, and thus, their absolute age is determined by an average of 6000 years.

The Holocene phase of the Black Sea development is divided into several phases: the first - old Black Sea phase began during the establishment of a bilateral connection between the Black and Mediterranean seas (8.5-9.5 thousand years ago). During the old Black Sea phase, the level of the Black Sea experienced a synchronous rise of the ocean level and reached its modern level about 6000 years ago. By that moment, the old Black Sea phase of the development of the Black Sea basin has ended, during which the level of the Black Sea did not rise above its current level.

The Neo-Black Sea phase of the development of the Black Sea basin began about 6000 years ago and lasted until the period of 3700-3500 years ago, when the level of the world ocean and the Black Sea was slightly higher compared to modern times. After the New Black Sea phase of the Black Sea basin development, the Phanagorian regression started. The reason for the development of this regression was the process of global cooling of the climate, known as the late Subboreal cooling. One group of researchers believes that the Phanagorian regression stopped at the turn of the Old and New Eras or in the first centuries of the New Era. However, according to the results of the paleogeographical interpretation of the archaeological and geomorphological facts related to the coastal settlements of the Adriatic and Hellenistic periods along the eastern coasts (Pazisi, Gyenos, Dioscuria, Panticapeia, Phanagoria, Chersonese, etc.), the Phanagorian regression should be ended earlier - in the IV-III centuries BC. At the turn of the Old and New Eras, the Nymphaeian Transgression contemporary to the Dunkirk Transgression of the World Ocean started in the Black Sea Basin and continued until the 10th-12th centuries of the New Era during which the sea level was raised 2-3 m above the mark during the Phanagorian regression (Janelidze 2008; Janelidze 2015).

The process of modern global warming begins at the end of the 19th century. It is estimated that over the last 100-120 years, the average annual air temperature on the earth's surface has increased by an average of 0.7-0.8 degrees. In this period, the increase in the annual average temperature of the air caused the level of the Black Sea to rise by 18-20 cm. This fact is confirmed by the data of long-term level measuring stations (including in Batumi and Poti) located on the Black Sea coast.

Anthropogenic impact

The dynamics of the coastal zone of the Black Sea in Georgia was significantly influenced by the anthropogenic impact due to which the natural contours of the coast formed over many hundreds of years have changed significantly. This impact continues today. Human activities such as harbor construction, coastal urbanization, road and rail infrastructure building, river modification, HPP development, and extraction of minerals (inert materials) from rivers, beaches, and underwater slopes. Improper planning and implementation of coastal protection measures have significant negative impacts. Factors such as intensive deforestation in river basins, draining of swamps to promote agriculture and construction of canals on the Kolkheti plain are also worth noting.

The process of disruption of stable development of the coastal zone started at the beginning of the 20th century that was caused by accelerated agricultural exploitation of certain areas of the coastal zone. The gradual expansion of coastal settlements, the construction of roads and various structures on and along the coast led to the gradual deterioration of conditions for stable dynamic development of the coast. Construction of harbors in the cities of Poti and Batumi at the end of the 19th century and in Ochamchire in the 30s of the 20th century should be mentioned. The breakwater dams and walls built to protect the inner aquatory of these harbors from waves and to prevent them from solid sediments have dramatically impeded and completely stopped the movement of shoreward flows of solid sediments on some sections of the coastline. In this way, these harbors gave way to experiencing a shortage of beach-forming material on a significant part of the coastal zone and strengthening the beach wash-away process.

The strengthening of the anthropogenic degradation process of the coastal zone was also facilitated using various types of rigid constructions (underwater and above-water concrete walls, stone breakwater, etc.) designed to protect the beach wash-away. Such type of embankment facilities were placed in the most active wave crashing zone - in the upper part of the underwater slope, on the beach and on the outer edge of the shore, which further hindered the process of movement of solid sediment along the coastline.

The construction of hydro power plants (HPPs) and their reservoirs played a particularly negative role in disrupting the natural development regime of the coastal zone, which significantly reduced the amount of solid sediment carried by rivers to the coastal zone. The situation was aggravated by the extraction of large amounts of inert material from riverbeds, low-lying floodplains, beach strips, and shores. By approximate calculations, in the 20th century, more than 30 million m^3 of inert material was extracted from the beaches and shores of the coastal zone of Georgia, due to which the ability of the above-water land of the coastal zone to resist wash-away has significantly decreased.

From the morphodynamical point of view, the coast of Georgia is divided into dynamic systems of Abkhazia, Poti and Chorokhi rivers. The coastal zone of Abkhazia was stable until the 30s of the 20th century. In 1933-34, the breakwater dam built to protect the inner aquatory of the harbor from waves in the northern part of Ochamchire, blocked the flow of beach-forming sediment moving along the shore from the Kodori River estuary to the Enguri River estuary. As a result, in the coastal zone to the south to the Ochamchire harbor, an acute shortage of beach-forming sediment occurred and an intensive beach wash-away process began. In the following years the process of coast erosion was intensified along the coastal edge of the city of Ochamchire, just as a result of the improper construction of tens of wave-reflecting concrete walls (so-called “dykes”) built to prevent the wash-away (Janelidze, 2015).

Based on the analysis of the topographical maps of 1872, 1933, 1957 and the topo geodesic materials of the 80s of the 20th century, it was established that a large part of the continuous strip of beach and coastal ridges that existed between the rivers Ghalidzga and Enguri until the 30s of the 20th century, were completely washed away by the sea and the coastal land was retreated by 100-170 m. (Janelidze, 2015).

The situation is also unfavorable to the north of the Kodori River estuary where a significant shortage of beach-forming sediment is observed. This is due to the extraction of a large amount of inert material from the coastal zone and surrounding areas. Currently, compared to the 80s of the last century, the sediment shortage has been increased by three times and more. According to the 2011 data of the Agency of Geology and Mineral Resources of the Autonomous Republic of Abkhazia, the land line was retreated by 50-120 meters for two decades (Janelidze, 2015).

The construction of HPPs also caused significant damage to the coast of Abkhazia. The construction of Sukhumi HPP had a negative impact on the amount of solid sediment of the Gumista River. Within 1948-1964, 51,900 m^3 of sediment was accumulated in the East Gumista reservoir, and the amount of solid sediment in the river was decreased by 20-25% (Jaoshvili, 2002).

Enguri HPP, the construction of which started in 1961, had a very negative impact on the coastal zone. Engurhi HPP was put into operation in 1978 and finally was completed in 1984. It is still the largest of the existing hydro power plants in Georgia (272 m high arch dam with installed capacity of 1300 MW, average installed annual output of 4340 million kWh, total volume of the reservoir - 1100 million m^3, useful volume - 680 mln m^3. Enguri HPP is a power plant created with a dam-derivative scheme. The scheme also included the 220 MW Vardnili HPP I and three similar HPPs (Vardnili HPP II, III and IV each with a capacity of 40 MW). The main flow of the Enguri River from the reservoir built near town of Jvari is dumped into the bed of the Eristskali River through tunnels and aqueducts. As a result of the HPP operation, water consumption was decreased from 165 m3/s to 39.5 m3/s. At the same time, the amount of inert materials brought into the estuary by the river was decreased by 83% (Jaoshvili, 2002). Before the construction of Enguri HPP, the coast from Ganmukhuri to Kulevi was fed by solid run-off from Enguri. Coastal erosion has developed from the place where the Enguri River water flows into the Black Sea after derivation (Blatter, & Ingram, 2001). The signs of the coast wash-away is observed at a distance of 4-5 kilometers to the south from the Enguri estuary (Gaprindashvili, 2019). The level of the riverbed rose, and at the estuary, near Anaklia, sea waves created sand ridges about 2.5 km long and 100 m wide, which also contributed to the wash-away of the shoreline. Geomorphological changes are also caused by the presence of an underwater canyon near the Enguri estuary (M. Kodua, 2016). The coast of the village of Anaklia and to the south began to retreat. The maximum wash-away was 180 meters. Also, the underwater slope is eroding, the waves washed off the old hardened rocks (Gaprindashvili, 2019).

"Two main factors have affected the natural development of the Poti coast. The first is the construction of the Poti harbor in 1888 to the north of the then Rioni River estuary. The moles to the south and west of the harbor also limited the free migration of sediment along the coast and divided a unified lithodynamic system of Poti. This caused the movement towards the coast in the north of the harbor and the erosion processes were activated at the head of the Poti canyon. However, initially these processes were not intensive. The intensive movement of the underwater canyon towards the coast was recorded in the 1920s. The second factor was throwing the Rioni River to the north of the harbor in 1939 to protect Poti from floods. Due to this, the harbor tended to occur inside the delta. This had a stronger impact on the coast development: the shore washed away to the south of the harbor and the accumulation to the north became intense. Up to now, about 300 ha of land has been lost on the southern coast, while the northern coast has increased by 1200 ha approximately" (Gaprindashvili, 2019)

Another factor affecting the Rioni delta is hydro power plants (HPPs). Several HPPs/cascades were built on Rioni and its tributaries: Rioni HPP (1933), Gumati HPP (1958), Lajanuri HPP (1960), Vartsikhe HPP (1971). Gumati HPP had a particularly significant impact on the reduction of river sediment, which in fact halved this indicator (Jaoshvili, 2002). According to N. Gaprindashvili (2019), "accumulation was the most powerful in 1939-1952: during this period, 114 million m^3 of sediment was accumulated, the increase of land was 533 ha, i.e., the average annual accumulation was 8.74 million m^3." In the following years, the volume of accumulation was decreased four times that was probably caused by the construction of Gumati and Vartsikhe HPPs in 1956-1973. In the 1980s, the volume of accumulation was increased, though it was still 2.5 times less than in 1936-1952. In the recent period, the annual volume of accumulation has increased again, although it is only 48% of the volume of 1936-1952.

As it seems, this dynamic was influenced first by the construction of Gumati and Vartsikhe HPP cascades, whose dams stopped the movement of sediment, and then in following years - by filling these dams with sediment. As a result, today these dams are no longer able to hold additional solid sediment which moves downstream more easily and is accumulated to the north of the Poti port. In addition, the erosion of the Rioni banks was intensified below the HPPs, which also strengthened the siltation process to the north of Poti.

One of the important impacts is the extraction of inert materials from riverbeds and terraces. For today, 134 mining licenses have been issued in the Rioni river basin that extract total of 5.2 million m^3 of raw materials (stone, gravel, silt) annually. This significantly affects the environment and ecosystem services. The vast majority - 95 licenses (71%) are issued immediately on the Rioni River. The total extractable volume defined by these 134 licenses is almost 20 million m^3. According to the instrumental measurements carried out in the 1980s, the average annual solid runoff of the Rioni River (both aerated and bottom) at the station of Sakochakidze (currently Mukhuri) was ≈ 13,285 thousand m^3. Today, mining companies extract 38-39% of sediments from rivers every year that has a significant negative impact on the Black Sea coastline (Kobalia, 2022).

According to data of 1978, out of 30 million m^3 of solid sediment brought into the Black Sea by the rivers from the territory of Georgia per year, 17 million m^3 are from Chorokhi only, which is 57% of the total sediment (Janelidze, 2015). The Chorokhi River had a very significant importance for the Black Sea coastal zone. It brought 83% of sediments, which determined the shape of the shoreline of this part of the Black Sea (Berkul et al, 20120. From the north of Chorokhi River estuary - up to the Natanebi River estuary, the solid beach-forming sediments moved smoothly along the coast. A single (continuous) dynamic system was formed. According to episodic planning materials, in the 30s of the 19th century the shore was on average 100-120 meters ahead (200-500 meters near the village of Adlia) (Janelidze, 1996, Kiknadze, Janelidze, Tatashidze 2000, Lominadze et al, 2013).

According to the map of 1834, the Chorokhi River flowed into the sea with three branches: one branch from the current Chorokhi estuary in the direction of Batumi, in 3.5 kilometers from the village of Adlia - the so-called Mejinistskali. The second branch was in the current estuary, and the third – in 1.5 kilometers to south of the current Chorokhi estuary, in the direction of Gonio. Such arrangement of branches led to the distribution of Chorokhi sediment in such a way that a large part did not fall into the underwater canyon. The sediments from the Gonio and Mejiniskali branches was completely used to feed the coast. The coast had a sharp arc outline and was naturally stable (Gaprindashvili 2019).

In the second half of the 19th century, in order to protect the surrounding area from Chorokhi river floods and flows, the Mejini branch was blocked with an earth dam. As a result, Chorokhi sediment was distributed to the two remained branches in the south. With this change, the largest part of the sediment moved towards the underwater canyon, and in fact, the supply of sediment to the central part of the Chorokhi-Batumi coast was stopped. The balance of the moving beach-forming sediment has changed dramatically that led to the coastline changes (Lominadze, Papashvili, Khorava 2013). In 1906, a 170-meter-long concrete embankment was built on the Batumi cape to protect the Batumi harbor aquatory from siltation. It contributed to accumulation of sediment towards Batumi Boulevard and played a positive role in sustaining and increasing beaches along the old Batumi Boulevard. For about a century, to the south of the harbor, the land within the borders of Batumi advanced by about 200 meters (Janelidze, 2015). On the other hand, because of the harbor mole, the movement of solid sediment to the north has been stopped that caused the wash-away of the coastal land.

In 1975, the south - Gonio branch of Chorokhi was blocked. As a result of these modifications, the whole river run-off fell into one central branch 70-100 meters away from the deep canyon of Chorokhi. The largest part of the beach-forming sediment (2 million m^3) fell directly into the deep canyon and could no longer participate in the beach formation process. The annual volume of beach-forming sediment participating in the dynamic processes of the coastal zone of Adjara was reduced to 0.4-06 million m^3. The coast of Adlia located to north of the Chorokhi estuary started to retreat intensively that was related to the alignment of the Chorokhi-Batumi coastline (Alpenidze, Lomtatidze 2011).

Another serious problem is caused by the construction of hydro power plants on the Chorokhi River and other rivers in its basin. According to a scientific article published by Turkish scientists in 2012, the southwestern region of the Black Sea is under severe threat of coastal erosion and shoreline recession caused by human activities. Due to the hydropower plants/dams built in Turkey, the amount of solid sediment brought to the beach has been decreased by 98%. 83% of this sediment was brought by the Chorokhi River, which determined the shape of the river and sea coastline in the region (Berkun et al, 2012).

According to the Chorokhi-Adjaristskali River Basin Management Plan (2016), the HPP dams built in Turkey reduced the natural beach-forming sediment of Chorokhi by 63%, which was 400 thousand m^3/year before the river was regulated. According to the same source, the construction of new dams in Turkey is expected to reduce the cost of solid sea beach nutrient sediment by an additional 20%. Through indirect effects, such as sand-gravel extraction and bed erosion, these HPPs will reduce run-off by another 12%. “Therefore, through the impact of the Turky’s HPPs and the insignificant impact of the Kirnati HPP, the sediment of Chorokhi will decrease up to 95%. If we add the extraction of sand and gravel for industrial purposes and the indirect impact of HPPs, the sediment will decrease up to 2% and the sea will practically lose its natural food source until 2025.”

In the monograph “River Hydro Construction and Geomorphological Processes of the Black Sea Coast of Georgia” (Gagoshidze, Kodua, Saghinadze, Kadaria, 2017), the construction of HPPs in both Turkey and Georgia is considered as a special threat to the coastal zone. According to the monograph, exploitation of the energy potential of the Chorokhi River in Turkey started in 1998 with the construction of the 249 m high arch dam of Deriner, which was completed in 2013. “According to the data of 2017, within the territory of Turkey, in total, construction of 27 dams is planned on the Chorokhi River, six out of which, in addition to Deriner, - Muratli, Borçka, Artvin, Arkun, Güllübağ and Tortum dams have already been built and commissioned in the Chorokhi basin. After commissioning HPPs that are planned or are under construction on the 26-kilometer section of the Chorokhi River on the territory of Turkey and Georgia, “the Chorokhi River will practically no longer provide beach-forming sediment to the coast of Adjara for 300-350 years.”

“Currently, the cascade of HPP dams launched on the territory of Turkey in the upper reaches of the Chorokhi River, as well as the construction of river-bed type HPPs on the last 26 km section of the Chorokhi River on the territory of Georgia, threatens the Gonio-Batumi section of the sea coast of Adjara with catastrophic wash-away” (M. Kodua, 2016).

Geological structure

The area adjacent to the Black Sea coast of the Kolkheti plain (as well as the Kolkheti plain as a whole) is an area of intensive accumulation of the waste material. This is due to its structural features, namely the Rioni river intermountain flexural line, which has been subsiding since the Neogene period until now. The tectonic subsidence of the land is compensated by the accumulation of waste material carried by rivers from the Caucasus main watershed and the Adjara-Imereti ridges towards the Kolkheti plain. Accumulation is particularly strong along the coastline, where sediment accumulation, along with land tectonic subsidence, is facilitated by the inhibiting influence of sea level as an erosional base on surface water drainage. The accumulated waste material was constantly subsiding under the influence of tectonic movements. The horizons of this material formed in the past are located at different depths from the earth surface.

In the Black Sea coastline, from the land surface to the 35-42 m to the depth, the horizon of sediments accumulated in the Holocene era is developed, under which 10,200-10,500-year-old peat piles are fragmentally buried (Janelidze 2008, 2015).

From the Tsikhisdziri cape to the extreme northern part of the Pichvnari (pine forest) resort area (city of Kobuleti) and to the north of the Pichvnari resort area – to the Natanebi River estuary, the upper part of the underwater slope of the coastal zone (50-70 m wide strip along the shore, max. sea depth 5 m) is built with gravel, stones and sand from the bottom surface to a depth of 20 m. At a distance of 200-400 m from the coast (sea depth 5-20 m), the underwater slope is built with silty sands to a depth of 10-12 m from its surface, which is replaced by silty clays further down.

Within the borders of the Pichvnari resort area, the largest part of the coastal plain between the coastal sections of the Dekhva and Choloki rivers is covered by peat swamps, where a single horizon of peat with a thickness of 5-9 m is developed (Janelidze, 2007; Janelidze, 2015).

A strip of ridges (dunes) between the Natanebi River and the canal connecting the Paliastomi Lake to the Black Sea to a depth of 10-12 m from the surface is built up with silty sands, which contain abundant mollusc fauna remains. A significant part of the narrow 400-600 m wide strip of the coastal plain located behind these ridges (to the east) is covered by Grigoleti and Maltakva peat bogs. The thickness of the single peat horizon of these bogs is within the limits of 5-9 m. (Janelidze 2015)

Under the area of the Rioni River estuary, in particular, the surface of the coastal land in the central part of Poti city, silty sands are developed to a depth of 10-12 m that are gradually replaced by swamp clays and loams. In the eastern part of the city, bog clays are mainly developed. (Janelidze 1996, 2015, Janelidze, Mikadze 2015)

In the structural basin of the Paliastomi Lake, a silty clay sapropel horizon is developed from the surface of the lake bed to the depth of 3 m on average, under which there is a propellant peat. To more depth, up to 18-20 meters, a horizon of monotonous silty sands is recorded. (Janelidze 1996, Janelidze 2008, Janelidze 2015)

Between the estuaries of Rioni and Churia rivers and also Churia and Enguri rivers, a strip of narrow coastal ridges (dunes) from the surface to a depth of 10-12 m is built with fine and medium grain silty sands. Imnati, Fichori, Shavtskala, Nabada, Churia and Anaklia peat bogs cover a significant part of the coastal lowland of the Kolkheti plain, directly adjacent to the strip of coastal ridges. The thickness of the single peat horizon of these swamps is on average 5-7, the maximum is 10-12 m.(Janelidze 1996, Janelidze 2015).

Geomorphological characterization

In the southern part of the Kolkheti plain, Kobuleti and Natanebi coastal lowlands are developed. They are stretched between the Kobuleti ridge, the hilly strip of Guria and the Black Sea basin. This part of the plain has a triangle outline, the base of which coincides with the Black Sea coastline and the tip intrudes as a wedge to the Natanebi River at a distance of 10-12 km from the coast. The western edge of the coastal plain follows the shore almost in a straight line. In the east, the surface of the valley rises slightly and in some places it cuts into the river valleys developed in the foothills of the Kobuleti ridge.

In the coastal zone between the Tsikhisdziri Cape and the Dekhva River estuary (southern district of Kobuleti city) a beach built with pebbles, medium and fine stones and a continuous strip of coastal dunes are developed. On this coastal section, there are two ridges formed at different times, with an average height of 3-6 m. The initial appearance of their surfaces has been greatly changed by facilities of various purposes. The surface of the coastal accumulative plain, located behind the coastal ridges, has also been significantly changed, which is completely used for agricultural purposes except for small single areas.

Along the Pichvnari resort area, behind the beach covered with pebbles, there are roughly separated ridges formed at different times. Their height ranges within 4-7 m. The width of the coastal land, covered by coastal ridges, is 200-300 m in this section.

Accumulative plain adjacent to ridges, the coastal part of which is a perfectly flat surface, is used for arable land and pastures. To the east, a large part of the coastal plain is covered by peat swamps, the surface of which is 2-4 m lower than the coastal ridges.

The terrain of the coastal zone between the estuaries of the Natanebi and Supsa Rivers is covered by a sandy beach with an average width of 30-40 meters. There and relic sand ridges across the shore. The height of the coastal ridge developed along the beach varies between 3.5-5.8 meters. The second coastal ridge is 50-100 meters away from the first and is evidently higher. At certain places its maximum height reaches 11-12 meters. In this section of the coastal zone of the Kolkheti plain, the strip of coastal ridges is the highest within the borders of the Black Sea coast of the Caucasus.

In the given section, the flat surface of the coastal plain (height 1.6-3.5 m.) merges with the ridge strip, which is distinctly separated from rather steeply sloping edge of the sand ridge. To the east, the coastal plain is gradually uplifted and overlaps the western edge of the Guria hilly strip.

Between the estuaries of the Supsa and Enguri rivers, the shoreline has an insignificant absolute height. The flat land surface of 2-3 km wide directly on the shoreline is elevated by 0.3-1.5 m above the sea level. There are also sections that are 0.1-0.3 m below the sea level.

Along the coastline, from the Supsa River estuary to the Canal connecting the Paliastomi Lake with the Black Sea, a continuous strip of sandy beach and coastal ridges are stretched over. Two ridges of different ages are well expressed in the terrain, their height reaches 6-7 meters near the Supsa River estuary and decreases to 2.2-2.8 meters to the north. The total width of the ridges and the beach on this coastal section is 200-400 m.

In this area, a very low coastal plain edges with the strip of sand ridges, a significant part of which is covered by Grigoleti and Maltakva peat swamps. In the recent past these swamps were singled out by a perfectly flat surface and rich wetland vegetation. Currently, their natural appearance is disturbed by human intervention. In fact, instead of peat swamps puddles of different sizes and shapes filled with water and secondary swamps have appeared.

To the north of the Rioni River estuary, a continuous strip of sand ridges stretches along the shoreline, the height of which does not exceed 1.8-2.0 m on average, and the width varies within 200-300 m. The primary morphology of ridges is significantly altered by pits appeared as a result of extraction of large amounts of sand for construction purposes.

The coastal zone between the estuaries of Khobi and Churia rivers, is the only area whose terrain has been less affected by human economic activity. In this area, a strip of sand ridges has been preserved in an almost natural form (width 150-200 m., height 2-2.5 m.). The peak of the ridge strip has a flat surface. It descends steeply towards the beach and slopes rather sharply towards the inland swamps (Janelidze 2015).

The morphology of the coastal zone between the estuaries of the Churia and Enguri rivers has been changed less. In some parts of this coastal section there are two relict ridges between which the depression along the shoreline is covered by several small, elongated lakes. Among them, Kharkalu Lake is the largest (length 280 m, width 30-50 m). In this area the natural appearance of the land terrain of the coastal zone has been significantly changed due to the influence of the anthropogenic factor (dirt roads, sand quarries, and facilities of various purposes).

A sandy beach stretches in a continuous strip between the estuaries of the Rioni and Enguri rivers. On this section of the coast, the beach is almost unaffected by abrasion and maintains a constant width (30-40 m) along its entire length. The width of the beach increases only at the river estuaries. For example, its width at the Khobi River estuary is 80-100 meters, and at the Churia River estuary reaches 100-150 meters (Janelidze 2015).

Morphodynamic regions

In forming the morphological characteristics of the coast of the Black Sea of Georgia, the movement of the waste material brought to the coastal zone by rivers (Psou, Bzipi, Gumista, Kodori, Enguri, Chorokhi) on the underwater slope and its accumulation along the coast is of essential importance. This process, together with the sea wave regime and the geological structure of the coast, determines modern outline of the coast, the peculiarities of under-water and above-water terrain of the coastal zone.

Waste material moves on the underwater slope in two directions: from north to south - from the Psou River estuary to the Khobi River estuary, and from south to north – from the Chorokhi River estuary to the Supsa River estuary. The coastal zone of the central part of the Kolkheti plain between the estuaries of the Supsa and Khobi rivers (length 30 km) is the central area, which is divided into two parts by the old estuary of the Rioni River: the southern part continues up to the Supsa River estuary, and the northern part – to the Khobi River estuary.

From the morphodynamic point of view, the coast of Georgia is divided into dynamic systems of Chorokhi, Poti and Abkhazia rivers. These systems, in turn, are divided into subregions.

In the recent past, beaches of Adjara coastal zone along the entire length was supplied with large fractional materials (pebbles, stones, gravel) brought into the sea by the Chorokhi River. The flow of waste material along the river banks moved from the Chorokhi River estuary to the north and reached the Natanebi River estuary. As a result of the development of accumulative processes on the underwater slope, Batumi (Burun-Tabie) cape began to move gradually towards the sea that caused a delay in the movement of the onshore flow of waste material to the north. Due to the construction of mole with a length of 170 m, the flow movement was deteriorated significantly in 1885-1892 at the continuation of the Batumi harbor and then the Batumi cape.

The terrain of the underwater slope of the coastal zone between the Tsikhisdziri cape and the Natanebi River estuary in the southern and northern parts of the subregion is relatively simple. The angle of the underwater slope surface in this section is 0.3-0.4 degrees. In the central part of the subregion (Pichvnari resort area), the source of the Kobuleti underwater canyon flows closer to the shoreline, therefore the surface of the underwater slope of the coastal zone is steeply inclined towards the sea. From the Tsikhisdziri cape to the Natanebi River estuary the underwater slope is covered with pebbles and gravel to the depth of up to 3 m; deeper, up to 10-12 m, sands and silt are developed. The beach is mainly built with the Chorokhi River material - pebbles, gravel and partially sands (porphyrites, andesites, basalts, tuffs); sands are increasing on the surface of the beach from the Tsikhisdziri Cape towards the Natanebi River estuary. On the surface of both the beach and the underwater slope to the north of the Natanebi River estuary, the number of pebbles and gravel decreases significantly, they are replaced by sand. However, the river Chorokhi material (pebbles and gravel) is observed in insignificant quantities on the surface of the beach at one km distance to the north of the Natanebi River. (Janelidze 2015).

The most southern part of Poti's dynamic system (Natanebi subregion) covers a 12-km zone between the estuaries of Supsa and Natanebi rivers. In this section, the surface of the underwater slope of the zone is mostly flat, with a slight inclination towards the sea. At the depth of 10-15 m, the surface of the underwater slope is covered with sand, which at depth is replaced by silt. At the Supsa River estuary the morphology of the underwater slope is complex. Here at the seashore, the source of the Supsa underwater canyon appears which starts at the depth of 6-7 m and descends rather steeply towards the sea, with an angle of 20-30 degrees.

To the north of the Natanebi estuary, material of the Chorokhi River is no longer observed in the surface structure of the beach and underwater slope. In the coastal zone of Nataneb subregion which is the southern part of the Poti dynamic system, the beach and underwater slope are mainly built with the fine-grained material brought into the sea by the Natanebi River, more than half of which are medium-grained sands. Here, the sediments forming the beach have a high, 4-11% composition of magnetic sands. A significant part of the waste (mainly fine-grained sands) carried by the Supsa River into the sea is lost in the Supsa underwater canyon. Therefore, the role of this material in the construction of the beach from the estuary of the river to the south is not significant (Janelidze, Mikadze 2007).

A continuous strip of 30-80-m width is developed within the borders of the Natani subregion. Due to the impact of wave crashing, it is not washed away significantly and is distinguished by its relatively natural sustainability.

The coast of the Poti dynamic system's subregion located between the estuaries of the Supsa and Khobi rivers is oriented along its entire length (30 km) at a right angle towards the westerly waves that prevail here most of the year. As a result, there are no permanent coastal currents on the underwater edge of this subregion. The Poti harbor divides this area into southern and northern regions. The southern region is bounded by the Supsa River and the Rioni River underwater canyons to the north. The surface of the shelf with a width of 8-10 km between them is covered with sandy gravel to the depth of 8-15 m. The steepness of the underwater slope surface is very insignificant (Janelidze, Mikadze 2007).

A continuous beach strip between the estuaries of the Supsa River and Maltakva Canal that connects the Paliastomi Lake to the sea is mostly stable. At a distance of about 5 km to the north of the Supsa estuary, the width of the beach is 40-45 m. On this part of the coast, only minor local wash-away occurs. To the north of the Maltakva Canal estuary, the coast is mostly stable for a length of about 3 km. The width of the beach in this section is 40-50 m. When approaching the southern branch of the old estuary of Rioni, the shoreline washes away intensively about 1 km along (Janelidze, Mikadze 2007).

In the northern region of the Rioni River (between the Poti harbor and the Khobi River estuary), the surface of the underwater slope of the coastal zone is flat and slightly inclined towards the sea. Underwater slope to the depth of 10-15 m is covered with fine-grained sands of the Rioni River, and then is replaced by silt in the more depth. The beach on this coastal section is mostly covered with fine-grained sand, while the beach at the Khobi River estuary is built with the material carried by this river (fine-grained sands, silt).

To the south of the Khobi river estuary, at a distance of about 10 km, the energy equivalent of the wave crashing is oriented at an almost direct angle to the coastline. The coastline stretches in a straight line from north to south. There is no movement of the underwater flow of the constantly acting dissolved material along it. This section of the coast is characterized by a stable mode of development of morpho-lithodynamic processes. The beach having a width of 35-50 m on average is not washed away.

To the south, at the new estuary of the Rioni River the width of the beach is increasing that is caused by delta moving forward. The width of the beach on this section of the coast on both sides of the estuary is about 100-120 m.

Coastal zone of between Khobi and Enguri estuaries (length 15 km) is the extreme northern subregion of the Poti dynamic system. The surface morphology of the underwater slope is similar to that of the area of the south section. At the estuary of the Enguri River, the surface of the underwater slope is sharply divided by the sources of the Enguri underwater canyon, which flow into the coastal zone in three branches at a distance of 130-150 m from the shoreline.

In the recent past (before the construction of the Enguri HPP) the river Enguri annually released about 370,000 m^3 of beach-forming material into the sea, most of which (about 65%) consisted of large and fine-grain sands. The width of the beach was 30-40 m. Throwing a large part of run-off from the Enguri river into the Eristskali river basin and the significant reduction of solid material at its estuary resulted in the strengthening of coastline wash away. Coastal wash away along the entire length of this area is slowly progressing until today (Janelidze, Mikadze 2007).

The influence of the anthropogenic factor on hydro and morphodynamic processes and their reflection on the coastal zone dynamics.

At the beginning of the last century, the development of morpho- and hydrodynamic processes in the Black Sea coastal zone (except for the abrasive coastal areas) took place mainly along the coastline, in the presence of excess beach-forming solid sediment of river origin. Rivers - Chorokhi, Rioni, Enguri, Kodori, Bzipi and others brought much more beach-forming material to the coastal zone than was necessary to maintain a stable dynamic equilibrium of the shoreline. Wash away process of the shoreline during strong storms was replaced by the accumulation of solid sediments along the coastline when the sea was calm, and the above-water land of the coastal zone regained its morphological characteristics that is has before storms.

Prevailing winds, Sea currents, Waves

The meteorological elements of the air of the Kolkheti plain (winds, precipitation, temperature, etc.) are determined by its location on the border of temperate and subtropical zones, the insignificant height of the plain, the ridge systems bordering it on three sides, the proximity of the Black Sea, etc. Under the influence of these conditions, especially the uneven heating of the surface of the coast and the sea and the presence of high ridges on the Black Sea coast contribute to the generation of winds of different directions and strengths. In the cold season, the eastern winds prevail on the seacoast, while in the warm season, the western (sea) winds prevail. Breezes are also observed in the coastal zone. During the year, the frequency of windy days is 32-38%. The average speed of the east föhns at the Rioni River estuary is 4.3 m/s, and the maximum exceeds 40 m/s. The average number of days with strong wind is 80-82 per year (Javakhishvili 1996).

In the formation of the coastal zone of the Black Sea of Georgia mainly transverse wave currents and coastal wave currents occur. Due to the frontal orientation of the coastline to the prevailing disturbances, transverse wave currents cause the movement of water mass towards the shoreline. As for coastal tidal currents, their movement along the coastline is caused by the oblique angle touch of waves with the shoreline. In such a case, the water mass moves along the coastline in a one-way direction. As a result, coastal currents on the coastline of the Black Sea of Georgia move in the following direction: from north to south - from the Psou River estuary to the Khobi River estuary, and from the south to the north - from the Chorokhi River estuary to the Supsa River estuary. As for the section from the Khobi River estuary to the Supsa River estuary (the central part of the coastal zone), the movement of the coastal currents is variable and moves both in north and south direction (*Fig. 2)*. (Janelidze 2015).

There are no particularly strong waves on the coast of the Black Sea of Georgia. Strong wave currents are mainly observed during the winter period, which are caused by 5-6 magnitude storm winds. The height of the waves, when splashing on the coastline, rarely exceeds 2-3 m. (Beridze 2008).

Solid run-off of major rivers, water consumption

Enguri	Average annual consumption before regulation – 192 m^3/s; after regulation - 50 m^3/s Solid material (beach forming material) before regulation - 369300 m^3, after regulation - 35000 m^3
Khobi	Average annual consumption - 50.5 m^3/s Solid run-off (beach forming material) – 39500 m^3
Rioni	Average annual consumption - 409 m^3/s Solid run-off (beach forming material) – 1350000 m^3
Supsa	Average annual consumption - 46 m^3/s Solid run-off (beach forming material) – 39,000 m^3
Natanebi	Average annual consumption - 33.5 m^3/s Solid run-off (beach forming material) - 18,000 m^3
Chorokhi	Average annual consumption - 277 m^3/s

Fig. 2. Bathymetry and local shore currents' direction

Methodology

The methodology developed for the assessment of the dynamics of the coastline change uses remote sensing and geoinformation technologies. The methodology used includes the delineation of the coastline contour using semi-automatic satellite image classification techniques. All historical coastlines are retrieved by processing satellite images from Landsat 4-5 TM, Landsat 8 OLI and Sentinel 2 satellite sensors. Historical image selection is based on image clarity (minimum cloud cover) and correct geo-referencing. All images are collected in a similar season. As a result of classification of historical satellite images, we differentiated land/water and retrieved historical coast lines. The dynamics of shoreline change was evaluated using the Digital Shoreline Analysis System (DSAS) developed by the United States Geological Survey (USGS).

Satellite imagery was selected and retrieved from open access databases: Earth Explorer (USGS) and Copernicus Open Access Hub. NDWI (Normalized Difference Water Index) was calculated using QGIS (open-source software). Regarding the identification/extraction of directly historical (1987-2021) coastlines, we used the Semi-Automatic Classification Plugin (SCP). And lastly, using ArcGis - DSAS (software tool) we evaluated the dynamics of the coastline change. In particular, shoreline erosion and accretion were identified, shoreline movement was assessed, and statistical parameters of shoreline change were calculated.

Satellite imagery used

There are many remote sensing satellites that differ in spectral and spatial resolution capabilities. They are both commercial and free satellites designed for scientific purposes. Free multispectral imagery can be downloaded through various internet portals and software (SCP, Copernicus, etc.). Digital archives are represented by the data of the last few decades, which are always updated and user available.

Landsat 4-5 TM

Since 1972, the joint U.S. Geological Survey / NASA Landsat series of Earth Observation satellites have continuously acquired images of the Earth's land surface. Satellites are being updated up to day. The Landsat Thematic Mapper (TM) sensor was carried on-board Landsat 4 and 5 from July 1982 to May 2012 with a 16-day repeat cycle, referenced to the Worldwide Reference System-2. Very few images were acquired from November 2011 to May 2012. Satellite decommissioning began in January 2013. Landsat 4-5 TM image data files consist of seven spectral bands. Spatial resolution is 30 meters for bands 1 to 7 (*Table 1*). Thermal infrared band - 6 was collected at 120 meters, but it was resampled to 30 meters. The approximate size of the scene is 170 km from north to south and 183 km from east to west.

Landsat 4-5	Wavelength (Micrometers)	Resolution (Meters)
Band 1	0.45-0.52	30

Band 2	0.52-0.60	30
Band 3	0.63-0.69	30
Band 4	0.76-0.90	30
Band 5	1.55-1.75	30
Band 6	10.40-12.50	120 (30)
Band 7	2.08-2.35	30

Table 1. Landsat 5 bands, wavelength and spatial resolution

Landsat 8 OLI

Landsat 8 Operational Land Imager (OLI) collects data with improved radiometric accuracy at 12-bit dynamic range, improving the overall signal-to-noise ratio. Landsat 8 was launched on February 11, 2013, with a 16-day repeat cycle referenced to the Worldwide Reference System-2. Landsat 8 provides medium-resolution imagery from 15 to 100 meters from the Earth surface and polar regions and operates in the visible, near-infrared, short-wave infrared, and thermal infrared spectrums. Landsat 8 captures more than 700 scenes a day. The OLI sensor collects image data for 9 shortwave spectral Bands over a 190 km swath (*Table 2*).

Landsat 8	Wavelength (Micrometers)	Resolution (Meters)
Band 1	0.433 – 0.453	30
Band 2	0.450 – 0.512	30
Band 3	0.525 – 0.600	30
Band 4	0.630 – 0.680	30
Band 5	0.845 – 0.885	30
Band6	1.560 – 1.660	120 (30)
Band 7	2.100 – 2.300	30
Band 8	0.500 – 0.680	15
Band 9	1.360 – 1.390	30

Table 2. Landsat 8 Bands, wavelength and spatial resolution

Landsat image archives are available on the USGS and other Internet portals.

Sentinel 2 Mission

Sentinel-2 is a multispectral Earth observation satellite developed by the European Space Agency (ESA) as part of the Copernicus Earth observation service. The Copernicus Sentinel-2 mission consists of two polar orbit constellations placed in the same sun-synchronous orbit, phased at 180° to each other. It aims to monitor the variability observed in land/sea surface conditions. The satellite has a wide swath width (290 km) and increased revisit time (10 days at the equator with one satellite and 5 days with 2 satellites under *cloud-free conditions,* which results in *2-3 days at mid-latitudes). With these characteristics, the Sentinel-2 satellite can continuously monitor changes on the Earth surface. Sentinel-2 satellites have been operational since 2015. The produced image data files consist of twelve spectral bands with a higher resolution of 10 m (Table 3).*

Sentinel 2	Wavelength (Micrometers)	Resolution (Meters)
Band 1	0.433	60
Band 2	0.490	10
Band 3	0.560	10
Band 4	0.665	10
Band 5	0.705	20
Band 6	0.740	20
Band 7	0.783	20
Band 8	0.842	10
Band 8A	0.865	20
Band 9	0.945	60
Band 10	1.375	60
Band 11	1.610	20
Band 12	2.190	20

Table 3. Sentinel-2 Bands, wavelength and spatial resolution

Sentinel-2 images are freely available on the ESA website:

https://scihub.copernicus.eu

Satellite image selection

Historical satellite images for our study were retrieved from satellite image repositories for the period of 1987–2021. Correct geo-reference, less cloud cover on the image, and seasonality were the necessary conditions for the selection of historical satellite images. All images were retrieved during the summer months (May to September). An additional parameter to consider was the same tidal phase to reduce the error of tidal effects.

The shoreline change analysis was performed in two different periods, based on the spatial resolution of the satellite images examined:

1. 15 Landsat 4-5 TM satellite images for nearly 21 years (1987 to 2008) were retrieved from the Earth Explorer database (USGS).
2. 3 satellite images were selected from the 2013 Landsat 8 OLI collection. Imagery were retrieved from the Earth Explorer database provided by the US Geological Survey.
3. Sentinel-2 12 satellite images covering a 6-year period (from 2015 to 2021) were retrieved from the Copernicus Open Access Hub, provided by Copernicus and the European Space Agency.

Below is a list of satellite images and data product specifications selected to assess the coastal erosion at the PONTOS pilot site in Georgia (*Table* 4). We selected and processed 30 satellite images. With few exceptions, all selected images were retrieved during the summer months. Exceptions are made for objective reasons, such as the low quality and lack of clarity of summer season images in conditions of intense cloud cover.

Data products	Number of images retrieved	Resolution	Years	File format	Data source
Landsat 4-5 TM	15	30 m	1987-2008	.TIF	*Earth Explorer, USGS*
Landsat 8 OLI	3	30 m	2013	.TIF	*Earth Explorer, USGS*
Sentinel 2	12	10 m	2015-2021	.TIF	*Copernicus Hub*

Table 4. Specifications and total number of data products

The study area is divided into 2 parts, the first part is located along the region of Abkhazia (where it is impossible to verify the field data), and the second part includes the shoreline of Adjara, Guria and Samegrelo-Zemo Svaneti (Fig. 3). 2 satellite images were selected and processed to extract each historical shoreline within the Abkhazia region, and 1 satellite image was selected and processed to extract the shoreline of Adjara, Guria and Samegrelo. Finally, 3 satellite images were selected to extract the shoreline of Georgia for each year (years of the study period). The detailed list of images selected is presented in the following tables: (Table 5, 6).

Fig. 3. Study area divided into sub-zones

#	Date	Data products	Resolution	Data collection	File format	Index
1	16-08-1987	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
2	13-08-1992	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
3	26-07-1997	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
4	25-06-2003	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
5	24-07-2008	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
6	7/8/2013	Landsat 8 OLI	30 m	OLI/TIRS Collection 2 Level-1	.TIF	NDWI
7	3/9/2015	Sentinel 2A	10 m	Sentinel-2 MSI Level_1	.TIF	NDWI
8	27/07/2017	Sentinel 2A	10 m	Sentinel-2 MSI Level_1	.TIF	NDWI
9	28-05-2019	Sentinel 2A	10 m	Sentinel-2 MSI Level_1	.TIF	NDWI
10	27-08-2021	Sentinel 2A	10 m	Sentinel-2 MSI Level_1	.TIF	NDWI

Table 5. Detailed list of selected satellite images. Regions - Adjara, Guria, Samegrelo-Zemo Svaneti

#	Date	Data products	Resolution	Data collection	File format	Index
1	4/6/1987	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
2	16-08-1987	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
3	4/8/1992	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
4	13-08-1992	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
5	26-07-1997	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI

6	18-08-1997	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
7	25-06-2003	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
8	3/8/2003	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
9	24-07-2008	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
10	1/9/2008	Landsat 4-5 TM	30 m	TM Collection 2 Level-1	.TIF	NDWI
11	23-08-2013	Landsat 8 OLI	30 m	OLI/TIRS Collection 2 Level-1	.TIF	NDWI
12	30-08-2013	Landsat 8 OLI	30 m	OLI/TIRS Collection 2 Level-1	.TIF	NDWI
13	27-08-2015	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
14	30-08-2015	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
15	27/07/2017	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
16	27/07/2017	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
17	17-07-2019	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
18	6/8/2019	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
19	25-08-2021	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI
20	28-08-2021	Sentinel 2A	10 m	Sentinel-2 mission Level_1	.TIF	NDWI

Table 6. Detailed list of selected satellite images. Region - Abkhazia

Shoreline extraction from satellite images

Historical satellite images were processed and historical shorelines were extracted using a semi-automatic classification method to identify land and sea areas based on their spectral signatures.

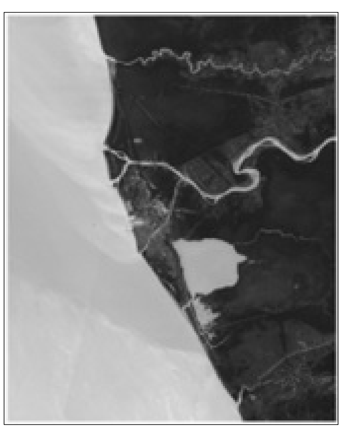
1. Normalized Difference Water Index (NDWI) introduced by McFeeters (1996), was used for the classification process. The NDWI index value is used to produce a binary classification of water/non-water areas. Since water bodies strongly absorb light in the visible and infrared electromagnetic spectrum, NDWI uses green and near-infrared bands to highlight water bodies. NDWI was calculated according to the McFeeters (1996) formula:

$$NDVI = \frac{(Band\ Green - Band\ NIR)}{(Band\ Green + Band\ NIR)}$$

For our study we used the following formulas:

$$NDWI_{L5} = (Band2 - Band4)/\ (Band2 + Band4)$$
$$NDWI_{L8} = (Band3 - Band5)/\ (Band3 + Band5)$$
$$NDWI_{S2} = (Band3 - Band8)/\ (Band3 + Band8)$$

2. NDWI resulted image was imported into the QGIS Semi-Automatic Classification Plugin (SCP) (Congedo, 2016) and approximately 15-20 regions of interest (ROI) were manually defined on each historical image by training the algorithm with two main macro-classes: Land and Water. The new raster file was further classified into two bands (Land and Water) using the minimum distance classification algorithm.
3. The shoreline was extracted by vectorizing classified raster image and further smoothing to better fit the coast.
4. The same process was applied for each historical satellite image and finally we extracted all the historical shorelines (*Fig. 4*).



Satellite image-NDWI

Classified image

Raster to Vector

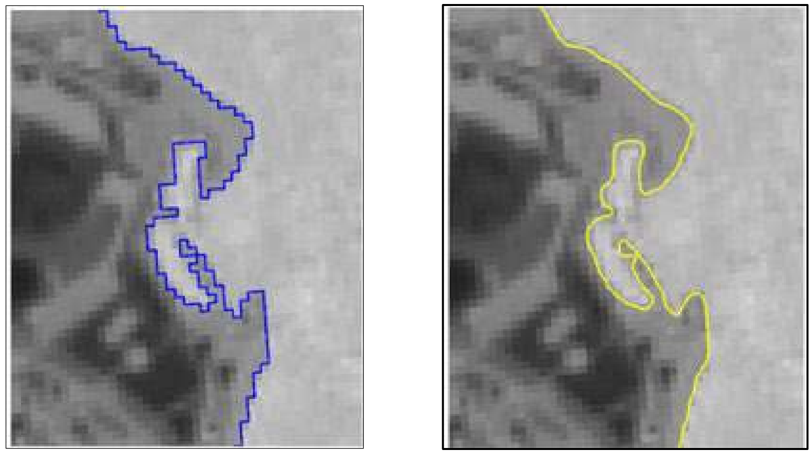


Fig. 4. Shoreline extraction sequence.

The final stage was validating the results obtained: assessment of accuracy of the semi-automatic classification method and error evaluation was conducted by comparing the shoreline extracted by the semi-automatic classification method, with a high-resolution WorldView-2 satellite image (spatial resolution 1.8 m).

Evaluation of shoreline change

Shoreline change was assessed using Digital Shoreline Analysis System (DSAS), provided by the USGS (Thieler et al., 2009). DSAS tool creates vertically positioned transects of the shoreline at a selected distance along the cost (in our case, 30 m). The baseline required by the DSAS tool to create transects parallel to the most recent shoreline (2021) was also established. Baseline and shoreline parameters were defined. In case of the baseline, the necessary condition was to determine the orientation (sea/land). In case of the shoreline, the exact date, crossing parameters and "uncertainty" were determined.

By statistical analysis of shoreline evolution over the study period (using data from DSAS transects), various statistical parameters were calculated and analyzed.

Accordingly, we obtained the main statistical indicators, such as:

SCE - represents the greatest distance between all shorelines that intersect a given transect (meters).

NSM - reports the distance between the oldest and the most recent shoreline for each transect (meters).

End Point Rate - EPR (in m/y) - calculated by dividing the distance of Net Shoreline Movement by the time elapsed between the oldest and the most recent shoreline.

Weighted linear regression (WLR, in m/y), in which the weight *w* is a function of the variance of the measurement uncertainty (Genz et al., 2007):

$$w = 1/e^2$$

where *e* is the shoreline uncertainty value.

The results were confirmed using the method of removing extreme values (based on the quantile of a distribution - 1%). The method is based on optical and empirical detection/finding.

Validation of satellite image classification method

Validation of the methodology of shoreline extraction from multispectral imagery was performed using a reference shoreline which is extracted from higher resolution satellite imagery. This image was obtained from the WorldView-2 sensor (panchromatic band with 0.46 m spatial resolution and 8 multispectral bands with 1.84 m spatial resolution). We used the shoreline extracted from the WorldView-2 satellite image as a reference shoreline because its accuracy is much higher compared to the Sentinel 2 and Landsat 8 OLI satellite images.

MAXAR's WorldView-2 satellite sensor (USA)[1] was launched on October 8, 2009 to observe and monitor the environment and it is still operating. The satellite is equipped with the most advanced technology sensor systems ever used in commercial remote sensing. The satellite operates at an altitude of 770 km and collects images with a panchromatic (black and white) resolution of 0.46 m and a multispectral resolution of 1.84 m. The satellite can collect multispectral imagery for more than 975,000 square kilometers per day. This capability is ideal for large-scale mapping projects. WorldView-2 can look at any point on Earth every 1.1 days or more.

The validation method was used to compare shorelines extracted from Landsat 8 OLI (30 m spatial resolution), Sentinel 2A (10 m spatial resolution) and WorldView-2 (1.8 m spatial resolution) (*Fig.5*).

[1] https://www.maxar.com/

Fig. 5. Satellite images (NDWI-index) used for the validation process

Sentinel 2A satellite image is selected for the same date and time as the WorldView-2 image. However, a Landsat 8 OLI image of the same date could not be selected because it was not available, thus the most recent available month and date were chosen (*Table 7*). Satellite imagery is similarly georeferenced and cloud cover is minimal. Distances between shorelines were estimated from vertical transects (2 m apart). Then, the distance between the intersect points was evaluated and the final statistical parameters were obtained accordingly (*Fig. 6*).

	Landsat 8 OLI	Sentinel 2A	WorldView-2
Date	29/08/2021	3/07/2021	3/07/2021
Resolution	30	10	1.8

Table 7. Satellite images selected for the validation process

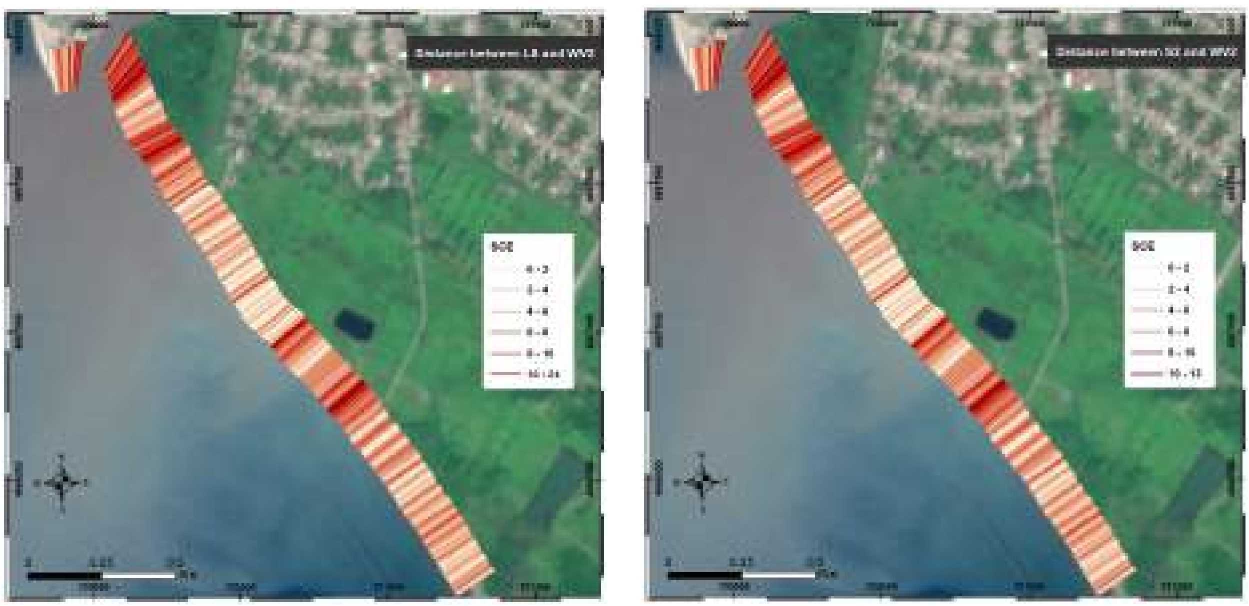


Fig. 6. Vertical transects showing the difference in coastal erosion estimates between WV2 and Landsat 8 OLI satellites (left panel) and WV2 and Sentinel 2A satellites (right panel).

The shoreline extraction methodology achieves a satisfactory and acceptable level of accuracy to the south of the city of Poti. The mentioned coast is characterized by a high level of erosion. That is why it is important to verify the accuracy of the shoreline of this area. Along the sandy (sandy-gravel) beach, the mean error in the Sentinel 2 image is about 4.9 m, and the maximum error value is 12.7 m (slightly larger than the one-pixel size (10 m)). It should be noted that an error of up to 2 m covers approximately 20%, while an error less than the mean, i.e., less than 5 m characterizes 55% of this study area, while an error larger than one pixel (>10m) is only 5%.

In the case of Landsat 8 OLI, the mean error is about 6,.6 m and the maximum error is 23.7 m (less than one-pixel size (30 m)). An error of up to 2 m covers about 15%, an error of less than

5 m characterizes about 41% of the shoreline, and an error of more than 15 m is only 5 % (*Table 8*).

In this area, satellite sensor performance is likely affected by the high concentration of suspended particulate matter (SPM) that prevails at the sea surface and is detected as land in the analysis.

	Landsat 8 OLI	Sentinel 2A
Mean error (m)	6.6	4.9
Maximum error (m)	23.7	12.7

Table 8. Table of the Shoreline position error extracted from Landsat 8 OLI and Sentinel 2A.

Shoreline Change Analysis

As mentioned above, the methodology we used to assess the dynamics of shoreline change as well as to determine its activity and identify “hot spots” along Georgia’s coastline, is based on the shoreline change analysis. The latter involves the processing of historical satellite images through remote sensing techniques and GIS software. Shoreline change dynamics were evaluated and statistical parameters were calculated using DSAS (software tool).

The shoreline analysis is used for the study of two time periods (1987-2013 and 2015-2021). Accordingly, different historical satellite products (Landsat and Sentinel images) with different spatial resolutions (30 m and 10 m) were processed.

1. Historical analysis of shoreline movement covers a 26-year period (from 1987 to 2013) with approximately 5-year time intervals. It should be noted that the accuracy of the interval is not observed due to objective reasons (poor quality of the image, or high degree of cloud cover on the image, which thus is useless for further processing)[2]. Satellite images from Landsat 4-5 TM and Landsat 8 OLI collection databases are used for the analysis. The spatial resolution of the satellite image bands for Green and NIR is 30 m. The images are retrieved from the Earth Explorer database (USGS).
2. The most recent analysis covers the period from 2015 to 2021 (with a 2-year time interval). Satellite images from the Sentinel 2 collection, with a spatial resolution of 10 m in the Green and NIR bands are used for the analysis. Satellite images are retrieved from the Copernicus Open Access Hub database.

Since we have divided the study area into 2 parts for the calculation of the shoreline change, the results of the coastline change analysis are also presented for respective parts of the study.

1. The first part covers the region of Abkhazia.
2. The second part includes Adjara, Guria and Samegrelo-Zemo Svaneti regions.

[2] *Note: It was intended to start the study from 1985, however the use of images of 1985 and 1986 was not possible due to high cloud cover. We could not use the 2002 image either.*

Figure 7 presents the main statistical parameters that define shoreline change and calculation based on a shoreline-perpendicular transect. The most important parameters of the shoreline change are:

1. Shoreline change envelope (SCE) - parameter represents the greatest distance between all shorelines that intersects a given transect (measurement units are in meters).

2. Net Shoreline Movement (NSM) - the parameter is the distance between the oldest and the most recent shorelines for each transect (units are in meters).

3. Weighted Linear Regression (WLR) - is an indicator of annual variation of coastline in meters. When using this algorithm, the more reliable data based on satellite image resolution are given more emphasis and weight in determining the best fit line. When calculating rate of change statistics for shorelines, more emphasis is placed on data points for which the position uncertainty is smaller (units are in meters/year).

The identification of accretion and erosive processes (*Fig. 8*), change intensity rate as well as change assessment (in km^2) for both parts of the study area according to the elapsed time between the oldest and the most recent shorelines are presented in the following chapters.

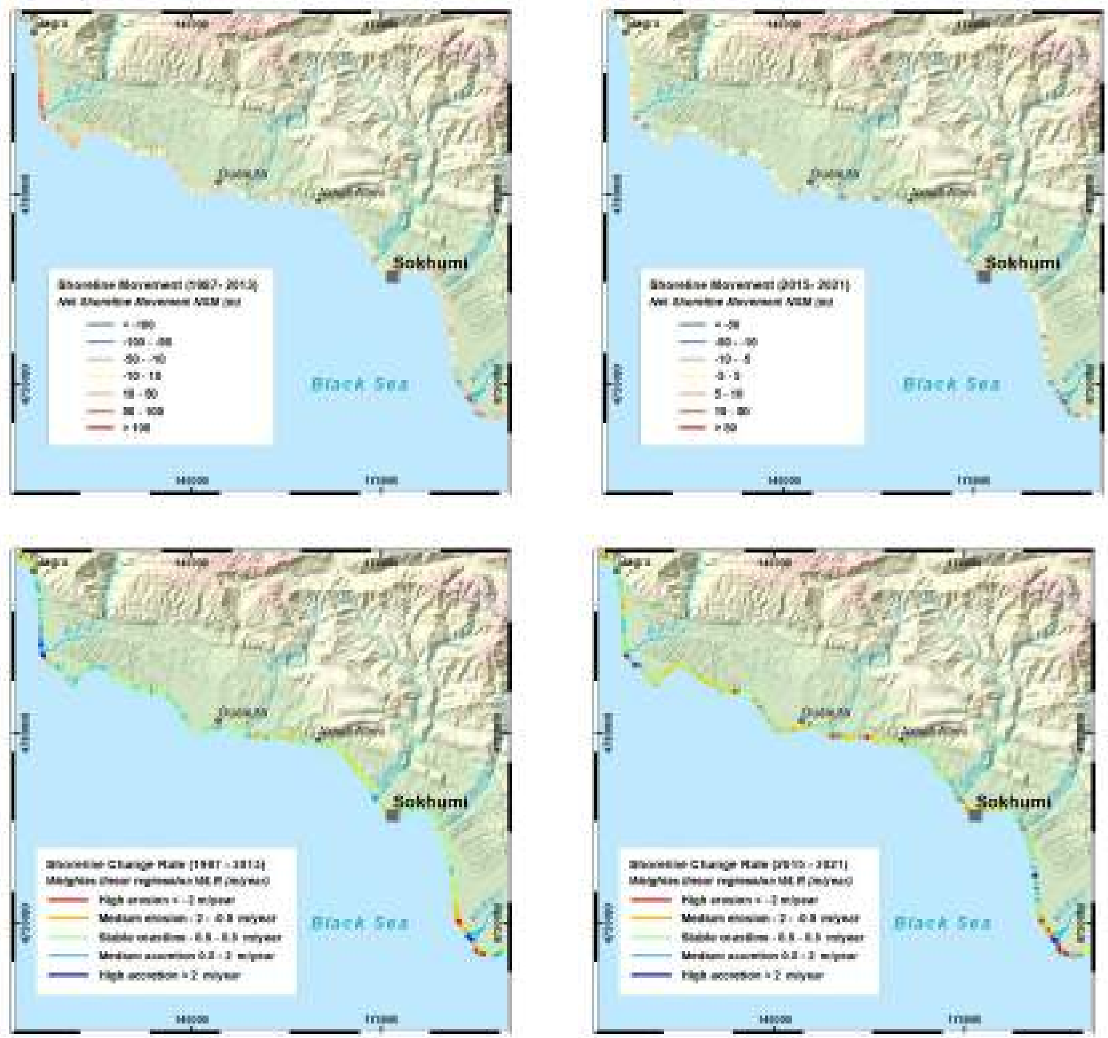


Fig. 7. Statistical parameters (SCE, NSM, and WLR) estimated: a) for the period from 1987 to 2013 (left panel) and b) for the period from 2015 to 2021 (right panel).

Fig. 8. Accretion and erosion processes from 1987 to 2021. On the left panel - accretion, on the right panel - erosion.

Results of the shoreline change analysis

Shoreline - Abkhazia

This shoreline covers the northern part of the study area. It stretches over 200 km and extends from the Psou River (border of Georgia) in the north to the Enguri River in the south.

Study Period 1987-2013

Statistical parameters describing the shoreline change from 1987 to 2013 with a time interval of approximately five years were estimated based on 6751 transects located perpendicular to the shoreline, with a distance of 30 meters between transects.

According to the analysis, erosive processes are approximately characteristic for 54.28% of the study area, while the remaining 45.72% are characterized by the land rise dynamics (*Annex: Fig. 1*). For a large part of this area (56%), the annual rate of shoreline change is stable and ranges from -0.5m to +0.5m, while almost 39% are characterized by moderate annual variation from -0.5m to -2m and 0.5m to 2m. Almost 5% of the shoreline is exposed to intense variability, the annual rate of which is more than 2m, out of which 2% of the shoreline is experiencing intense erosion. The average shoreline change (SCE) for this area is about 31.1 meters, the average NSM-distance between the oldest and most recent (1987-2013) years is 3.9 meters, and the average annual rate of erosion is (-0.04 ± 0.3 m/year), where 0.3m/year is the standard error. In the table below (*Table 9.*), the average, minimum and maximum values of significant statistical parameters of the study area change are presented.

	SCE	NSM	WLR
Average	31.1	3.9	-0.04
Minimum value	0.2	-123.7	-4.9
Maximum value	223.4	197.9	8.7

Table 9. Main statistical parameters of the shoreline change of Abkhazia (1987-2013).

As for the intensive change of the shoreline (> 2m/year), the most important hot spot of land increase is located along the right branch of the Kodori River delta (*Annex: Fig. 3*). Accretion rates reach an average (5.5 ± 0.3 meters/year). Sedimentation is up to 197 m, the area of land increase is 0.16 km². It is also worth noting that a maximum of 223.4 m of the SCE parameter (the largest distance between all shorelines which determines the dynamics of shoreline movement) is recorded in this area.

Also, in the 26-year data, at a distance of about one km to the south of the left branch of the Kodori River delta the shoreline retreat up to 121 m was recorded, the average erosion rate is almost (- 3 ± 0.3 meters/year), the area of land loss is about 0.08 km². About 500 meters from this area towards the Skurcha Lake, alternate sedimentation and erosion are recorded. The maximum rate of land increase is 120 meters, the average rate of accretion per year is (2.3 ± 0.3 meters), and the area of land increase is about 0.02 km². As for erosion: beach wash-away reaches 67 meters, the rate of erosion is on average (-2.6 ± 0.3 m/year), the loss of land extends over an area of 0.04 km² (*Annex: Fig. 3*).

It should be noted that the shoreline near the Bzipi River estuary is also characterized by a high average annual rate of land increase, approximately (3.8 ± 0.3 m/year), the rate of land increase in 1987-2013 is almost 160 m, and the increased land area is about 0.13 km².

From the Bzipi River estuary to the north up to the border of Georgia, the approximately 35 km shoreline is mainly characterized by stable and, periodically, moderate variability. Furthermore, from the Bzipi River estuary up to the Kodori delta the shoreline (100 km) is also characterized by stable and moderate variability, with the exception being the intensive erosion processes along the small Kodori estuary, with an average annual rate higher than -2 m. In particular, along the small Kodori River estuary approximately 2 kilometers north of the right branch of the Kodori River delta, erosion is recorded, the land loss is approximately 79 meters, the average annual rate of the shoreline change is (-2.6 ± 0.3 meters), approximately 0.06 km² of land has retreated.

Furthermore, the shoreline from Skurcha Lake located ~2 km south of the left branch of the Kodori River delta up to the Enguri River is mostly characterized by stable and moderate variability. A significant change is recorded only along the estuary of the Mokvi river, where the land increase is about 145 meters with the maximum rate of annual change (5.5 ± 0.3 meters), the area of the increased land is 0.15 km², and on the shoreline to the south of the Enguri canal estuary (*Annex: Fig. 4*), where the highest maximum rate of erosion is observed

(- 4.9 ± 0.3 m/year), and the average rate is (-2.8 ± 0.3 m/year), land loss is approximately 124 m (the maximum rate of the study area) and extends over an area of 0.07 km^2.

Study period 2015-2021

The statistical parameters that record the coastline change in Abkhazia from 2015 to 2021 with a two-year time interval were evaluated according to 6741 transects located perpendicular to the shoreline, with a distance of 30 meters between the transects.

According to the results of the analysis, 43.43% of Abkhazia's shoreline is characterized by land increase dynamics and 56.57% - by erosive processes of different intensity (*Annex: Fig. 2*). On the shoreline of Abkhazia, compared to the previous study years, an increase in erosion processes has been recorded since 2015 (2%). Furthermore, an increase in the dynamics of the intensity of the shoreline change is observed. A rather large part of the mentioned area (43%), which is 13% less compared to the previous study period, is characterized by a stable rate of shoreline change and ranges from -0.5m to +0.5m per year, and almost 47% is characterized with the annual moderate variability from -0.5m to -2m and from 0.5m to 2m. Moderate shoreline development is 8% higher compared with the previous study period. As for the intense variability of the shoreline, the annual rate of which is more than 2 m, the area is almost two times more than recorded in the previous study period and amounts to 10%, out of which 7% comes from erosion processes, which is three times higher than the data of the previous study period.

Average shoreline change (SCE) for this area for the 6-year period is approximately 10.7 meters, the average NSM is -2.6 meters, and the average annual rate of change is (- 0.2 ± 0.4 m/year), where 0.4 m/year is the standard error. In the table below (*Table 10*), the average, minimum and maximum values of significant statistical parameters of the study area change are presented.

	SCE	NSM	WLR
Average	10.7	-2.6	-0.2
Minimum value	0.01	-71	-18.2
Maximum value	152	98.3	23.7

Table 10. Main statistical parameters of shoreline change of Abkhazia (2015-2021)

Within a 6-year period, the most important indicators of the shoreline change have been recorded at the Enguri canal estuary where erosion processes observed during the previous study still continue, although the intensity has been considerably increased and the maximum annual erosion rate is about (-18 ± 0.4 meters) , the average rate is (-9.6 ± 0.4 m/year), the land loss is about 71 meters, and retreated land area is 0.02 km^2. However, to the south, erosion is replaced by accretion that was not recorded during the previous 26 years. The average annual rate of accretion is also high (7.3 ± 0.4 m/year), the sedimentation reaches 90 meters during the mentioned period (*Annex: Fig. 4*).

In the given period of study, hot spots of accretion have been identified along the Kodori River delta (in the previous period of study accretion was characterized to the coast adjacent to the right branch of the Kodori River delta). Here the rate of accretion is very high and reaches a maximum of about (24 ± 0.4 m/year), the average rate is (-9.5 ± 0.4 m/year), and the accumulation of sand between the oldest year (2015) and the most recent year (2021) is up to 98 m, the increased land area covers 0.09 km^2. As for the shoreline located to the north of the right branch of the Kodori delta, erosion processes have started with a value of average annual variability of erosion (-2.7 ± 0.4 m), and land loss is recorded up to 26 meters (0.01 km^2) (*Annex: Fig. 3*). To the north, at a distance of approximately 2 kilometers along the small Kodori River estuary, as in previous study, erosion has been recorded, and land loss reaches approximately 22.5 meters, the annual average rate of shoreline change is (-2.5 ± 0.3 meters), and the washed-off land area is 0.01 km^2.

Sedimentation along the Kodori River delta is replaced by erosional processes to the south, where the erosion rate is on average (-4.4 ± 0.4 m) per year, and the shoreline retreat is up to 35 m. Compared to previous years, the annual erosion rate has increased, the length of extension along the shoreline has also increased, and it stretches over 1.2 km of the shoreline. The washed-away beach covers an area of 0.04 km^2. Further south, towards the Skurcha Lake, alternate sedimentation/erosion is still recorded, with increased intensity. The maximum rate of land increase is 30 meters, the average accretion rate per year (4.2 ± 0.3 meters). As for erosion: the beach wash-away reaches 32 meters, the erosion rate is on average (-5 ± 0.3 m/year) (*Annex: Fig. 3*).

In the previous period of study, from the Bzipi River estuary to the border of Georgia in the north (the Psou River), the coastline of about 35 km was mainly characterized by stable and, periodically, moderate variability. According to the data of the last 6 years, accretion and erosion are recorded alternately to the south of the Psou River estuary. Sedimentation reaches 90 meters, the average rate of accretion change is (8.3 ± 0.4 m) per year, and the increased land area is 0.01 km^2. As for erosion, the annual average change is (-4.6 ± 0.4 m), and retreated beach reaches 40.5 meters.

As for the shoreline to north of the Bzipi River estuary, accumulation processes still continue since 2015 and, compared to the previous study period, are characterized by a higher average annual rate of accretion (about 4.5 ± 0.4 m), with an increased land area of 0.01 km^2. However, to the south of the Bzipi River estuary, instead of sedimentation, erosion processes are recorded and the land is washed-off up to 57 meters. A high average annual rate of erosivity is recorded (-4.2 ± 0.4 m/year), the area is 0.02 km^2. According to the study analysis of previous years (1987-2013), the shoreline change from the Bzipi River including the Bichvinta Cape was stable. From 2015, along the Inkiti relict lake, particularly on the beaches of Inketi village coast, erosive and accretion processes are recorded alternately. The land increase reaches 25 meters, the annual change is 3.5 meters on average. The land increase is replaced by erosion where, according to the data of the last 6 years, the loss of land reaches 25 meters, the annual average change in erosivity is -2.7 meters.

Since 2015, significant erosion processes have also started along the Aapsta River estuary. Average annual erosion rate is (-4 ± 0.4 meters), land retreat reaches 45.5 meters, and the area is 0.02 km^2.

Quite intensive erosive processes also occur on the shoreline near the village of Adzghapsha, which was characterized by stable development in previous years. The average annual erosion rate is (-2.8 ± 0.4 meters), beach retreat reaches 30 meters, the area of land loss is 0.01 km^2.

At the of the Gumista River estuary significant sedimentation, approximately 57 meters is recorded, the maximum annual accretion rate is 13 meters, the increased land area is 0.01 km^2.

The sediment accumulation process of the Kelasuri River is also recorded. Since 2015, there has been a land increase of 65 meters, with a high average annual accretion rate (5.9 ± 0.4 m).

In 1987-2013, the shoreline in the south from the Kelasuri River to the Kodori River was mostly characterized by stable and moderate variability. Since 2015, an intense land increase of 24.5m has been recorded to the north of Pshafi village, with the average annual rate of accretion (2.8 ± 0.4 meters).

In the previous study period, the shoreline of Abkhazia from Skurcha Lake located at 2 km south of the left branch of the Kodori River delta up to the Enguri River was mostly characterized by stable and moderate changes. A significant increase of the land was recorded only along the Mokvi River estuary, while erosion processes were observed on the shoreline to the south of the Enguri canal estuary. In the last 6 years, the stable and moderate change of the shoreline in this section has been replaced by intense changes. In particular, in the vicinity of the village of Lepona, land erosion reaches 32 meters, the annual rate of erosion is almost (-5 ± 0.4 m/year), the area is 0.02 km^2. In the previous study period, this area was characterized by a stable shoreline change (- 0.5 m to + 0.5 m/ year). Similarly, erosive processes are recorded at the estuary of the Dghamishi River. The annual rate of erosive change is (-4.5 ± 0.4 meters), while land loss reaches 28.5 meters.

As for the sedimentation at the estuary of the Mokvi River, it has been replaced with erosive processes since 2015, the maximum rate of land retreat in 2015-2021 is 24 meters, the average annual erosion rate (- 2.4 ± 0.4 meters). Only at the cape of the Ochamchire berth, the land increase is 70m, and the maximum annual accretion rate reaches 12 meters.

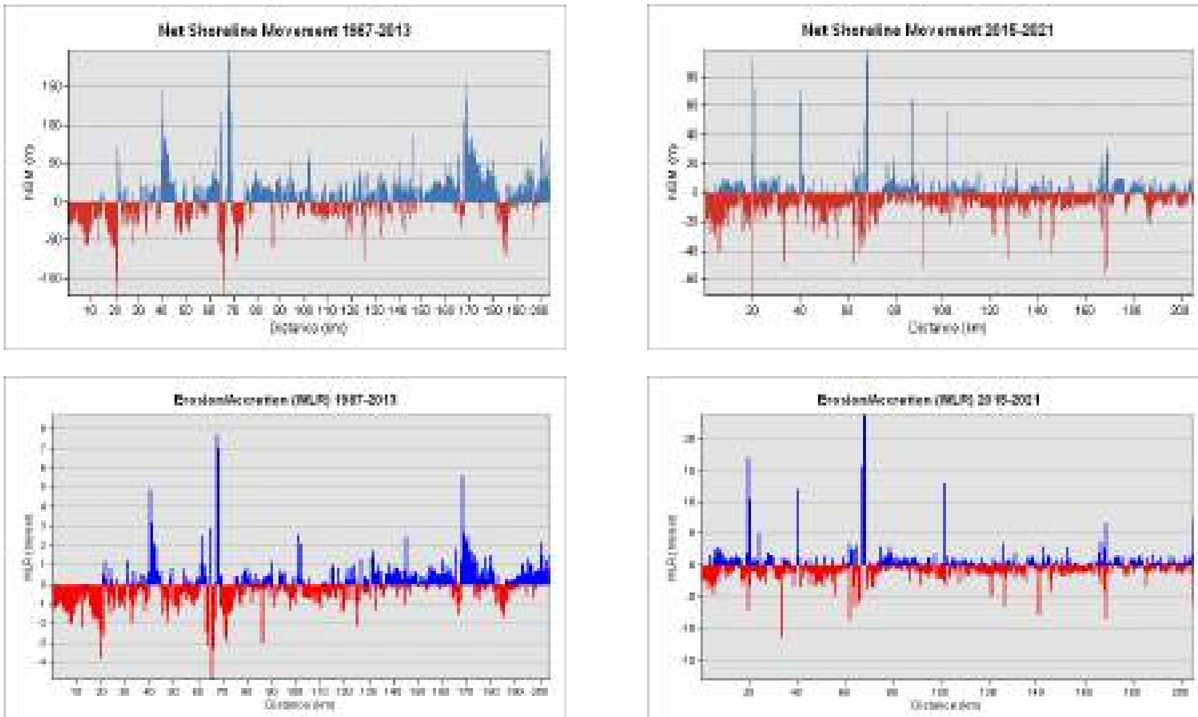
In the same period, near the city of Ochamchire, the right shoreline of the Ghalidzga River estuary is also subject to erosive processes, the beach wash-away is up to 50 meters, and the annual rate of erosion is on average (- 8.2 ± 0.4) meters.

The evolution of the shoreline of Abkhazia for both study periods in 1987-2013 and 2015-2021 is visualized in the form of graphs (*graphs 1, 2*), maps (*Fig. 9*) and tables (*Table 11*).

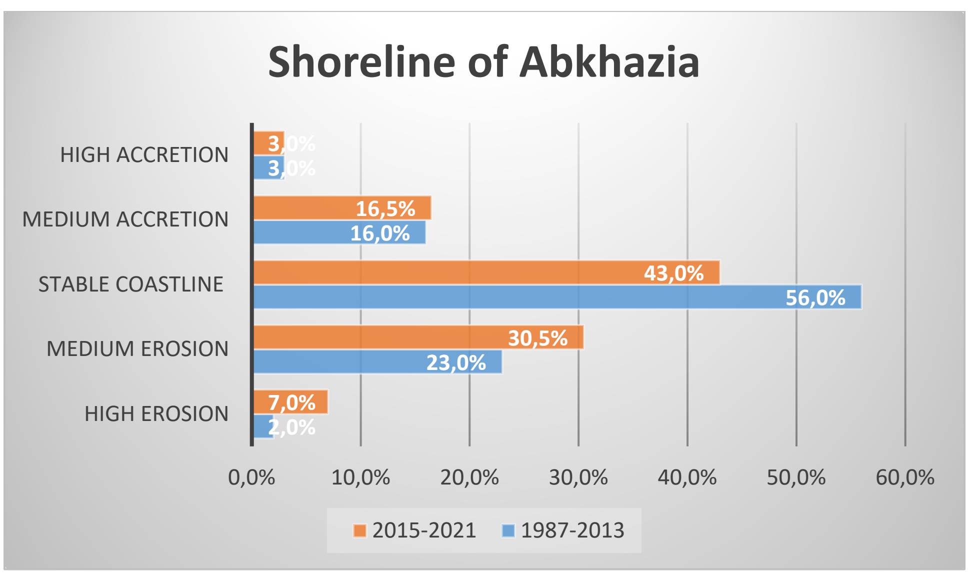
Average rate of change of coastline		
Period	**Average (in m/y)**	**Standard error**

1987-2013	-0.04	0.3
2015-2021	-0.2	0.4

Table 11. Average rate of annual change (m/year) of the shoreline of Abkhazia and standard error (according to study periods)



Graph 1. Upper panel: The graph shows Net Shoreline Movement (NSM) in meters for each transect along the shoreline for 1987-2013 (*left*) and 2015-2021 (*right*). The graph shows the statistical parameter of the annual shoreline change (WLR) in m/y along the shoreline for 1987-2013 (*left*) and 2015-2021 (*right*).



Graph 2. Percentage distribution of erosion and accretion according to intensity

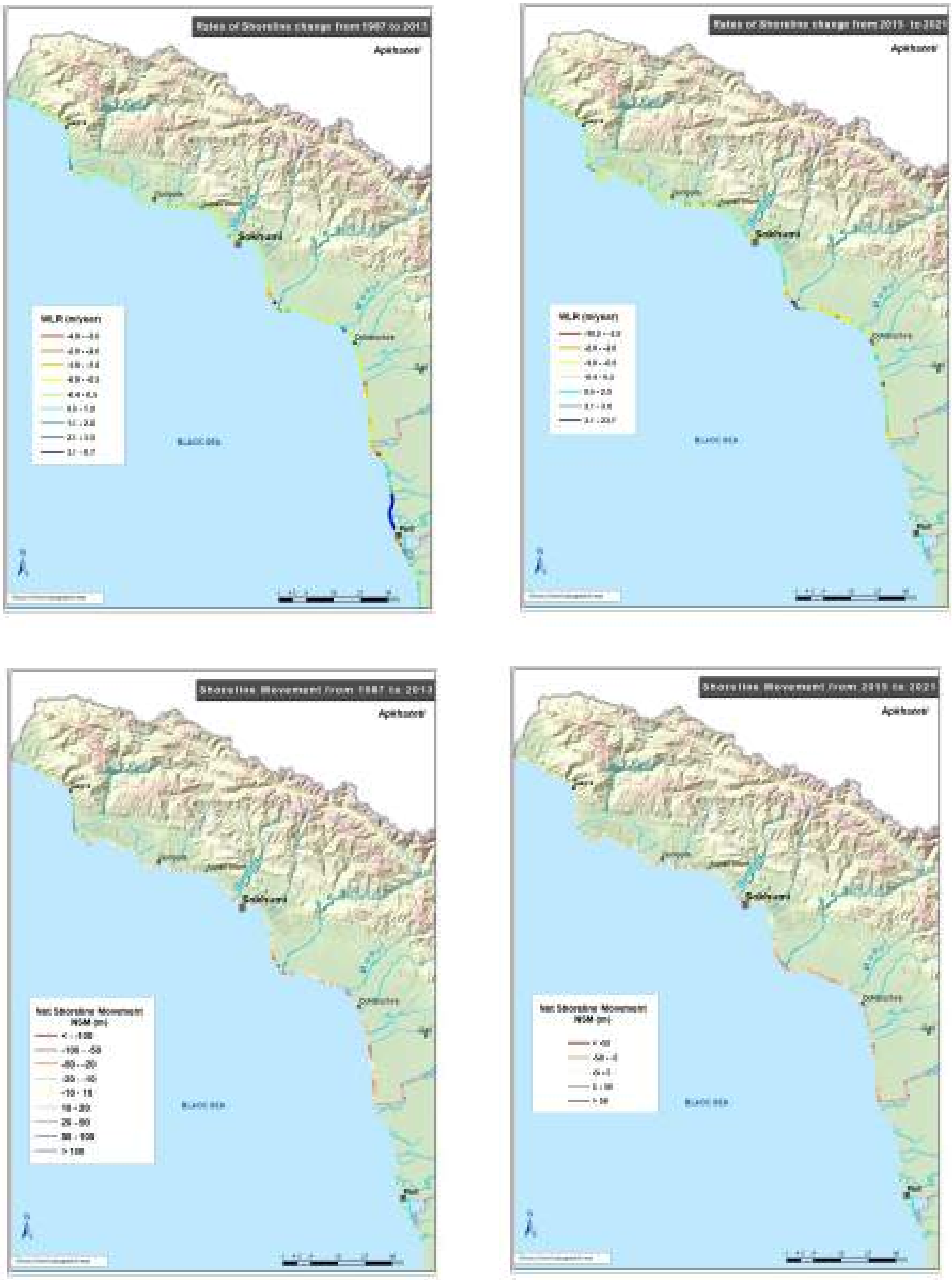


Fig. 9. Upper panel: Map of the annual change (in m/yr) of the shoreline of Abkhazia in 1987-2013 (left) and 2015-2021 (right). Bottom panel: Abkhazia shoreline movement (m) map in 1987-2013 (left) and 2015-2021 (right).

Shoreline - Adjara, Guria, Samegrelo

This shoreline is the central and southern part of our study area. It stretches over around 115 km and extends from the Enguri River in the north to the village of Sarpi (border of Georgia) in the south.

Study period 1987-2013

Statistical parameters describing the shoreline change from 1987 to 2013 with a time interval of approximately five years were estimated based on 3706 transects located perpendicular to the shoreline, with a distance of 30 meters between transects.

According to the analysis, the percentage of all transects of more or less erosivity value of the study area is 22.21%, while 77.79% of the remaining transects are characterized by the land increase dynamics (*Annex: Fig. 1*). The ratio between erosional and accretionary processes is very different and is dominated by land increase tendency.

In almost 29% of the area, the annual rate of shoreline change is stable and varies annually from -0.5m to +0.5m, while 49% is characterized by annual moderate variation from -0.5m to -2m and from 0.5m to 2m. Almost 22% of the shoreline is exposed to the intense variability, the annual rate of which is more than 2m that is significantly higher than the rate of the first part of the same study period. 6.2% of the shoreline experiences intensive erosion, which is also 3 times higher than the shoreline of Abkhazia during the same study period, although the shoreline of Adjara, Guria and Samegrelo experiences more intensive accretional (13.8%) changes. The average shoreline change (SCE) for this area is about 67.7 meters, the average NSM is 34.6 meters, the average annual rate of change is (1.4 ± 0.4 m/y), where the standard error is 0.4 m/year. The table below (*Table 12*) shows the average, minimum and maximum values of significant statistical parameters of the change in the study area.

	SCE	NSM	WLR
Average	67.7	34.6	1.4
Minimum value	1.6	-215.8	-8.4
Maximum value	474.5	474.5	19.8

Table 12. Main statistical parameters of shoreline changes of Adjara, Guria, Samegrelo (1987-2013)

As for the intensive shoreline change (> 2m/year), the most important erosion processes are recorded on the shoreline adjacent to the village of Anaklia to the south of the Enguri River estuary (*Box 1: Fig. 5*). The most significant loss of land in this area is recorded during the study period, about 216 m during 26 years, the maximum rate of erosion reaches (-8.4 ± 0.4 m/year), and the average rate is -6.1 ± 0.4 m/year. The spread of erosion along the shoreline is 1.1 km^2 in length, and the area of washed-off land is 0.17 km^2.

About a 12-km long section of the shoreline in the south of Anaklia up to the Khobistskali River estuary is characterized by stable and moderate variability. To the north, near the Khobistskali

River estuary erosion is recorded. Land loss reaches 145 meters, the average annual erosion rate is -3.7 ± 0.4 m.

The most intensive accretionary change of the shoreline (hot spot of land increase) not only for the mentioned part but also for the entire study area is recorded in the vicinity of the Rioni River delta (*Appendix 1: Fig. 6*). The land accumulation extends not only directly along the Rioni delta, but also in the north of the right branch of the delta (Nabada right branch) and reaches almost to the estuary of the Khobistskali River, also extends to the southern direction of the left branch of the delta up to the Poti port. The length of extension is about 12 km, the increased land area is 3.2 km^2. In 1987-2013, land advance is recorded at about 475 m, the rate of accretion is estimated from 1.6 m to 19.8 m/year, with an average value of about (11 ± 0.4 m/year).

In the vicinity of Poti city, immediately in the south of the Rioni canal estuary significant retreat of the beach is recorded. The average rate of erosion is approximately (-3 ± 0.4 m/year), the maximum land loss reaches 146 m. The length of extension along the beach is almost 3 km, the washed-off land area is about 0.25 km^2 (*Annex: Fig. 6*).

The right bank of the estuary of the Paliastomi canal that is connected to the Black Sea is characterized by land increase. The average annual rate of the shoreline change is (2.7 ± 0.4 m), the land increase reaches 95 meters. As for the left bank, on the contrary, erosive processes are developing where the retreat of the beach is 138 meters and the rate of erosive change is (-3 ± 0.4 m/year).

During this study period, in the south of the Paliastomi canal (~1 km), after the location of the above-mentioned erosion processes, approximately a 52-km long shoreline up to the Batumi cape is mostly characterized by stable and moderate variability. There are no significant changes on the shoreline, and thus the average annual rate of shoreline change (WLR) is 0.6 ± 0.4 m , while the average Net Shoreline Movement (NSM) from 1987 to 2013 is 16.5 meters.

As for the cape of Batumi and the city of Batumi, a 1.5-2-km section of the beach experiences an increase. The average rate of accretion is (2.7 ± 0.4 m/year), the land increase reaches 90 meters (*Annex: Fig. 7*).

From Batumi towards the Chorokhi River, erosive processes are recorded on the shoreline near the village of Adlia, where the average erosion rate is -2.8 ± 0.4 m/year and loss of land reaches 90 meters (*Annex: Fig. 7*).

Also, it should be noted that in the 26-year data, approximately in 500 meters to the south of the Chorokhi River estuary, the retreat of the coastline up to 118 m is recorded, the erosion rate is -3.2 ± 0.4 m/year on average. The beach wash away extends over 1.3 km in length, the area of land loss is 0.15 km^2. Immediately at the estuary, on the both sides, accretion is recorded. In the south, the accretion rate is on average 11 ± 0.4 m /year, and the sedimentation reaches 180 meters. To the north of the estuary, the intensity of accretion is lower, on average 2.5 ± 0.4 m/year, and the land increase is 124.5 meters (*Annex: Fig. 7*).

To the south, the above-mentioned erosion is replaced by a coastal strip of stable development (~1 km), at the coastline along Gonio, Anaklia and Sarpi moderate accretion processes are recorded. The average annual accretion is 1.4 ± 0.4 meters, the land increase reaches 65 meters, the maximum accretion rate is about 5.7 ± 0.4 m/year, 130 meters of sedimentation is recorded only on a 300-meter section of the shoreline to the south of Anaklia.

Study period 2015-2021

Based on 3724 transects located perpendicular to the shoreline (with a distance of 30 meters between transects), now the statistical parameters describing the shoreline change from 2015 to 2021 in a two-year time interval were assessed.

In the given period, the results indicators of the analysis are different. 70.65% of the shoreline is characterized by the land increase dynamics, and 29.34% is characterized by erosion processes of different intensity (*Annex: Fig. 2*). Over this shoreline, since 2015 a 7-percent increase in erosion processes has been recorded compared to the study period of previous years, however, accretion processes are dominated as it was also recorded in the previous research period. From 2015 to 2021, an increase in the shoreline change intensity dynamics is observed too. The rate of the shoreline change is stable for 24% of the mentioned area and varies annually from -0.5m to +0.5m, the latter is about 5% less compared to the period of previous years, while annual moderate change from 0.5m to -2m and 0.5m to 2m is characterized for almost 43.5%, and it is almost 6% less compared to previous years. Almost 32.5% of the shoreline is exposed to intensive variability whose annual rate is more than 2 m that is significantly higher (~10.5%) than the rate of previous years. Intensive erosion is characterized for almost 7 percent of the shoreline. The rate of intensive erosion is also higher than the rates of the previous study period, although in the given case intensive accretion is dominated as well. The average of all shoreline changes (SCE) for this area is about 18.8 meters, the average of shoreline change between the oldest and most recent (2015-2021) years (NSM) is 8.4 meters, the average annual accretion rate is (1.2 ± 0.4 meters/year), where 0.4 m/year is a standard error. The table below (*Table 13*) shows the average, minimum and maximum values of the significant statistical parameters of the study area change.

	SCE	NSM	WLR
Average	18.8	8.4	1.2
Minimum value	0.5	-106.6	-18
Maximum value	151.1	151.1	23.5

Table 13. Main statistical parameters of Adjara, Guria, Samegrelo shoreline changes (2015-2021)

During the last 6 years, to the south of the Enguri River estuary, in the vicinity of the village of Anaklia, the shoreline is still characterized by high erosive activities, the maximum erosion rate is still -8.4 ± 0.4 m/year, although the average rate is slightly less than -5 ± 0.4 m/year. The land loss is up to about 48 meters. It should be noted that during the previous study period the shoreline from the Enguri River estuary up to the Khobi estuary (~12 km), except for the erosive area of Anaklia, was characterized by stable and moderate variability, however, the intensity of variability has been noticeable since 2015 on the mentioned section of the shoreline. In a one-km section to the south of the estuary of the Enguri River, sedimentation reaches 102 meters, and the average annual accretion rate is about 11 ± 0.4 meters. The increased land area covers 0.07 km^2. To the north of the estuary, sedimentation reaches 27 meters, the average accretion rate is 3.3 ± 0.4 m/year, the increased land area is 0.02 km^2 (*Annex: Fig. 5*).

Furthermore, erosion and accretion processes alternately are developed to the south of Anaklia, on the beach of Tikori village. The average rate of accretion change is 4.5 ± 0.4 m/year, the land increase is almost 23 meters. In the south, accretion is replaced by erosion. The average rate of shoreline erosion is -2.3 ± 0.4 m/year, beach retreat is nearly 22 meters.

Also, along the Churia River estuary, sedimentation is recorded on both sides. The rate of accretion is on average 4.6 ± 0.4 m/year, and the maximum rate is 8 ± 0.4 m. The land increase is about 48 meters, the area of the increased land covers about 0.04 km^2.

In the middle section of the shoreline to the south of Churia River up to the estuary of the Khobistskali River, accretionary processes are recorded on an approximately 800-meter long shoreline. The average accretion rate is 4.4 ± 0.4 m/year, the sedimentation is 37 meters and the increased land area is 0.02 km^2.

As for the Khobistskali River estuary, according to the data of the study conducted in the previous years, the land loss was recorded in the north while moderate changes were recorded in the south. According to the data of the last 6 years, a moderate variability is observed in the north and a land increase tendency – in the south. The average rate of accretion is 2.7 ± 0.4 m/year, the accumulation of sand is up to 25 m.

Even further to the south, as regards the Rioni delta and its surrounding area, intensive accretion processes still continue during these 6 years (*Annex: Fig. 6*). The sedimentation extends along the shoreline over about 11 km and covers an area of 0.46 km^2. The average rate of accretionary change is still high, about 7 ± 0.4 m/year, and the maximum is up to 18 ± 0.4 meters per year. The land increase is recorded at 90 meters. The accumulated land still extends not only immediately along the Rioni delta, but also to the north of the right branch of the delta (the right branch of Nabada) and reaches almost to the estuary of the Khobistskali River, and also extends to the southern direction of the left branch of the delta to the Poti port. In the view of the general land increase, intensive land wash-off is observed at the estuary of the southern branch of the Rioni delta that was not recorded until 2015. The average rate of erosive change is -6.9 ± 0.4 m/year, and the maximum is -18 ± 0.4 m/year. Land loss is almost 107 meters, retreated land area is 0.02 km^2.

At the same time, erosion processes continue to the south of Poti. The average rate of erosion is the same as recorded in the previous study period and is up to (-3 ± 0.4 m/year), the retreat of the shoreline is about 38 m. The length of extension along the beach is almost 2.5 km, the loss of land area is about 0.06 km^2 (*Annex: Fig. 6*).

Since 2015, along the canal that connects the Paliastomi Lake with the Black Sea, accretion has been observed in both directions at a distance of about 3.5 km. The annual average rate of accretion is 7 ± 0.4 meters, land increase reaches 115 meters, the increased land area is 0.14 km^2. Consequently, it should be noted that unlike the previous study period, according to the data of the last 6 years, erosion processes have been replaced by accretion in the south of the estuary of Paliastomi canal.

Changes are obvious on the ~52 km section of the shoreline (approximately from Paliastomi canal up to the Batumi Cape), which was characterized by stable and moderate variability. According to the data of the last 6 years, there is an increase in land along the beaches of Maltakva and Grigoleti villages. The average annual accretion rate is 2.5-3 ± 0.4 meters, land increase reaches 24-27 meters. Even further south, the river along the Supsa River estuary the shoreline undergoes significant accretionary change in both directions. The rate of accretion is on average 3.9 ± 0.4 m/year, sedimentation is up to 80 m and it covers an area of 0.05 km^2.

Also, a significant change is observed along the estuary of the Natanebi River. In particular, the land increase is recorded to the north of the Natanebi River, the average accretion rate is 5 ± 0.4 m/year, the land increase is up to 46 meters. To the south, on the contrary, erosion processes have started. Erosive change is on average -3.6 ± 0.4 m/year and land wash-off is up to 34 meters.

Further south, along the estuaries of the Kintrishi and Dekhva rivers sedimentation is also recorded. The annual maximum accretion rate is 3.3 ± 0.4 m/year, and the average is 2.2 ± 0.4 m/year, the land increase is up to 23 m.

After the opening of the Coast Guard Batumi Base to the south of Korolistskali estuary in 2015, the artificial barrier disturbed the natural balance of the distribution of beach-forming material and caused accretion processes. The average rate of accretion change is 2.5 ± 0.4 m/year, the land increase reaches 24 meters.

As for the Batumi cape and Batumi city, according to the data of the last 6 years, approximately a two-kilometer section of the Batumi beach as well as a 300-meter section of the Batumi cape are experiencing an increase in land. The average rate of accretion is (2.5 ± 0.4 m/year), the land increase reaches 27.5 meters (*Annex: Fig. 7*).

From Batumi towards the Chorokhi River erosive processes are still observed on the shoreline near the village of Adlia where the average erosion rate is -3.2 ± 0.4 m/year (more intensive than in previous years), land retreat is up to 22 meters. However, intensive erosion is only spread over 300 meters (it covered ~1 km in the previous study period) and in the south it is replaced by intensive accretion processes that occurs along the shoreline of approximately the same length, with an average accretion rate of 3.2 ± 0.4 m/year and accumulation of 29 meters (*Annex: Fig. 7*).

In the last 6-year data, accretion is still observed on both sides of the estuary of the Chorokhi River. In the south, the accretion rate is on average 3.5 ± 0.4 m/year (the intensity is decreased compared to previous years), the sedimentation reaches 27 meters, while the intensity of accretion in the north of the estuary increases and is on average 16.2 ± 0.4 m/year, the maximum rate is 23.5 ± 0.4 m/year. The land increase reaches 151 meters, the increased land area is 0.02 km^2. Accretion is replaced by erosion in the north of Adlia, the average annual erosion rate is -5.8 ± 0.4 m/year, and beach wash-away reaches 60 m (*Annex: Fig. 7*).

In the south from the estuary of the Chorokhi river, accretion is replaced by erosion, beach wash-away extends over 1.2 km, shoreline retreat up to 43 m is recorded, the rate of erosion is -5.2 ± 0.4 m/year on average (more intensive than in previous years). The area of land loss is 0.04 km^2 (*Annex: Fig. 7*).

In the south, this erosion is replaced by a coastal strip of stable development at a distance of ~5 km and then in the south from Anaklia village towards the border, moderate accretion and erosion processes are observed alternately. Accretion is on average 1.4 ± 0.4 m/year, the land increase is 21 meters. Only near the Sisliskhevi River erosion is observed -2.1 ± 0.4 m/year, and loss of land reaches 25 meters.

The evolution of the shoreline of Adjara, Guria, Samegrelo for both study periods in 1987-2013 and 2015-2021 is visualized in the form of graphs (*graphs 3; 4*), maps (*Fig. 10*) and tables (*Table 14*).

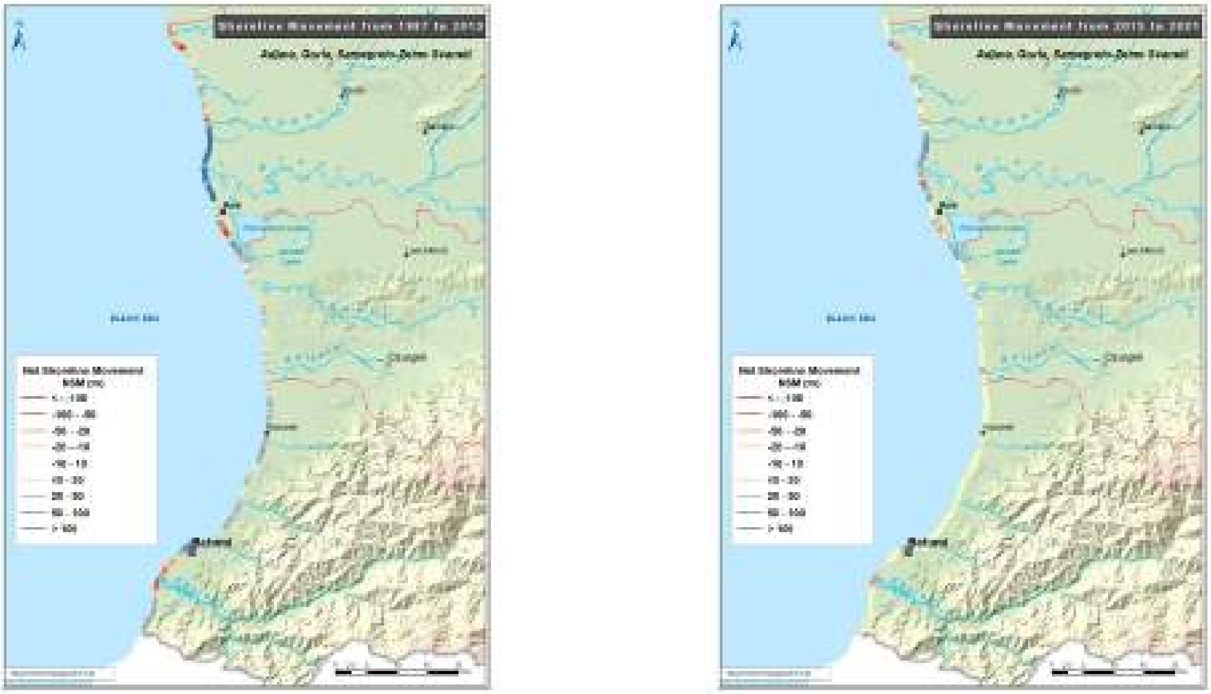
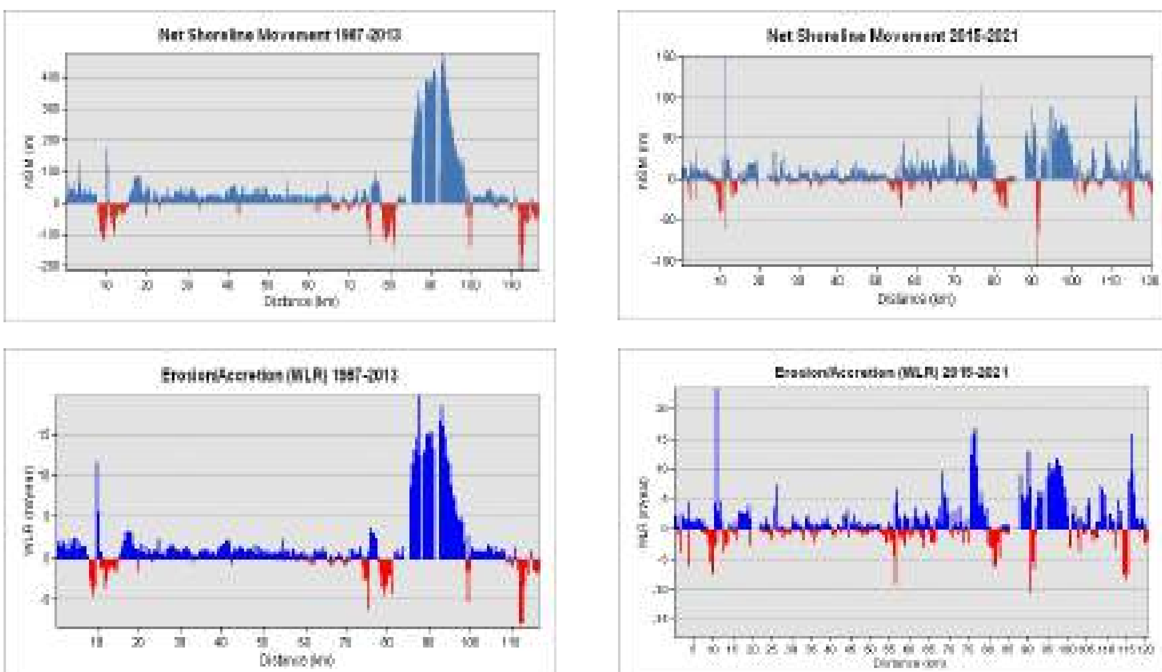
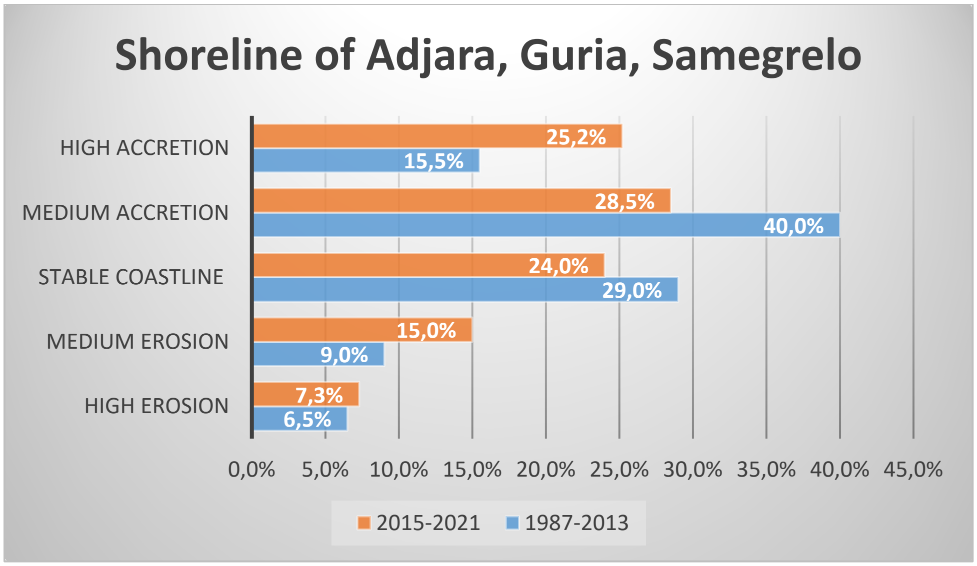


Fig. 10. Upper panel: Map of the annual variability (in m/y) of the shoreline of Adjara, Guria, Samegrelo in 1987-2013 (left) and 2015-2021 (right). Bottom panel: map of shoreline movement (in meters) of Adjara, Guria, Samegrelo in 1987-2013 (left) and 2015-2021 (right).



Graph 3. The graph shows the statistical parameter of the shoreline movement change (NSM) in meters for each transect along the shoreline for 1987-2013 (*left*) and 2015-2021 (*right*). The graph shows the statistical parameter of the annual shoreline change (WLR) in m/y along the shoreline for 1987-2013 (*left*) and 2015-2021 (*right).*



Graph 4. Percentage distribution of erosion and accretion according to intensity

Average rate of shoreline change		
Period	Average (in m/y)	Standard error
1987-2013	1.4	0.4
2015-2021	1.2	0.4

Table 14. Average rate of annual change of shoreline of Adjara, Guria, Samegrelo (m/year) and standard error (according to study periods).

Annex

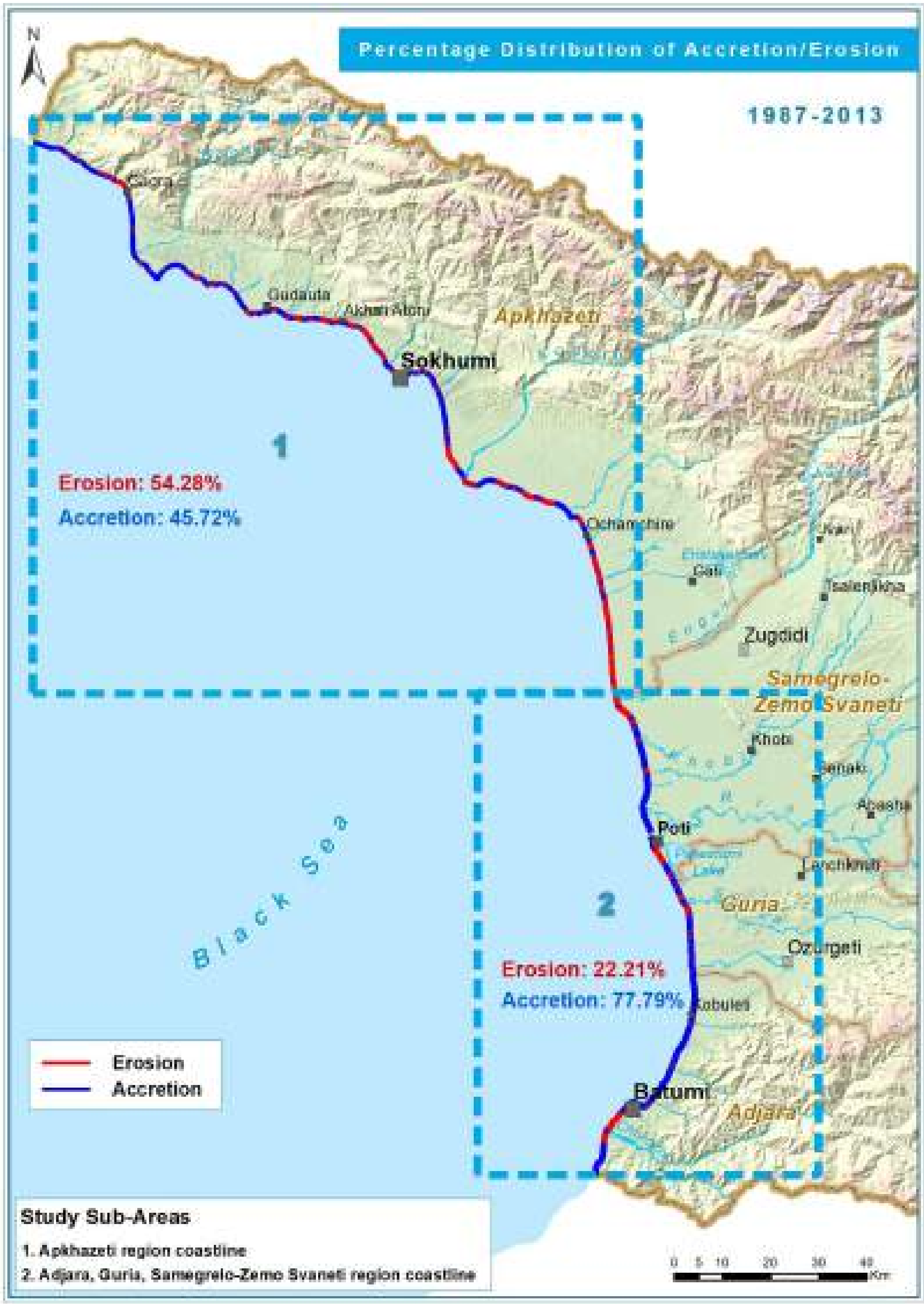


Fig. 1. Percentage distribution of erosion and accretion from 1987 to 2013

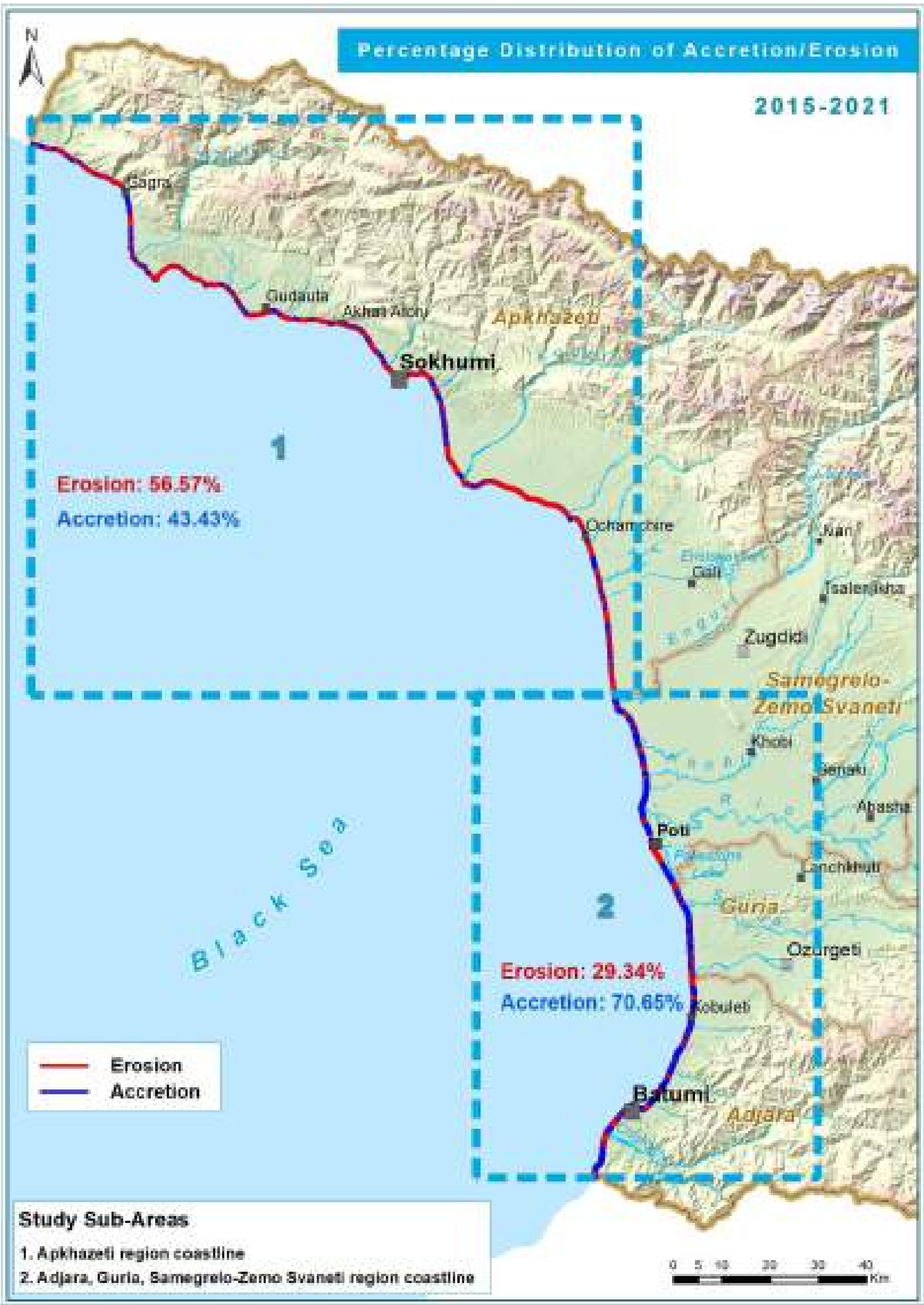


Fig 2. Percentage distribution of erosion and accretion from 2015 to 2021

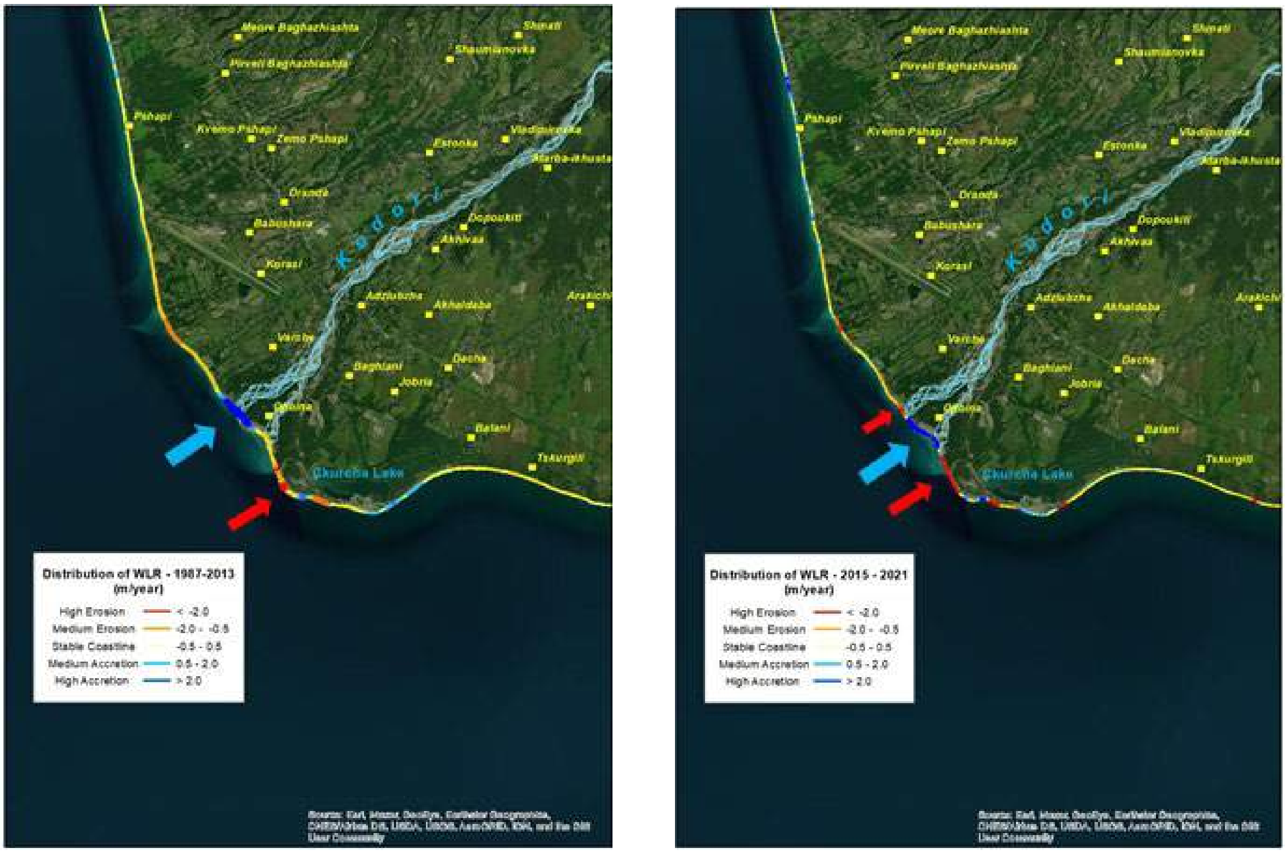


Fig. 3. Significant erosion/accretion of Abkhazia's shoreline. Left panel: 1987-2013. Accretion at the right branch of the Kodori river delta: WLR avrg. (5.5 ± 0.3 m/yr), NSM (197m); Erosion to the south of the delta: WLR Avrg. (-3 ± 0.3m/year), NSM (-121m); Right panel: 2015-2021. Accretion of the Kodori river delta: WLR avrg. (9.5 ± 0.4m/year), NSM (98m); Erosion to the south of the delta: WLR Avrg. (-4.4 ± 0.4 m/yr), NSM (-35 m); Erosion at the north branch of the delta: WLR Avrg. (-2.7 ± 0.4 m/yr), NSM (-26m). The shoreline towards Skurcha Lake undergoes intensive change.

Fig. 4. Significant erosion/accretion of Abkhazia's shoreline left panel: 1987-2013. Erosion at the Enguri canal estuary: WLR Max. (- 4.9 ± 0.3 m/year), avrg. (-2.8 ± 0.3 m/yr), NSM (124m). Right panel: 2015-2021. Erosion at the Enguri canal estuary: WLR Max. (-18 ± 0.4 m/year), avrg. (-9.6 ± 0.4 m/year), NSM (-71 m); to the south, erosion is replaced by accretion: WLR average (7.3 ± 0.4 m/yr), NSM (90 m).

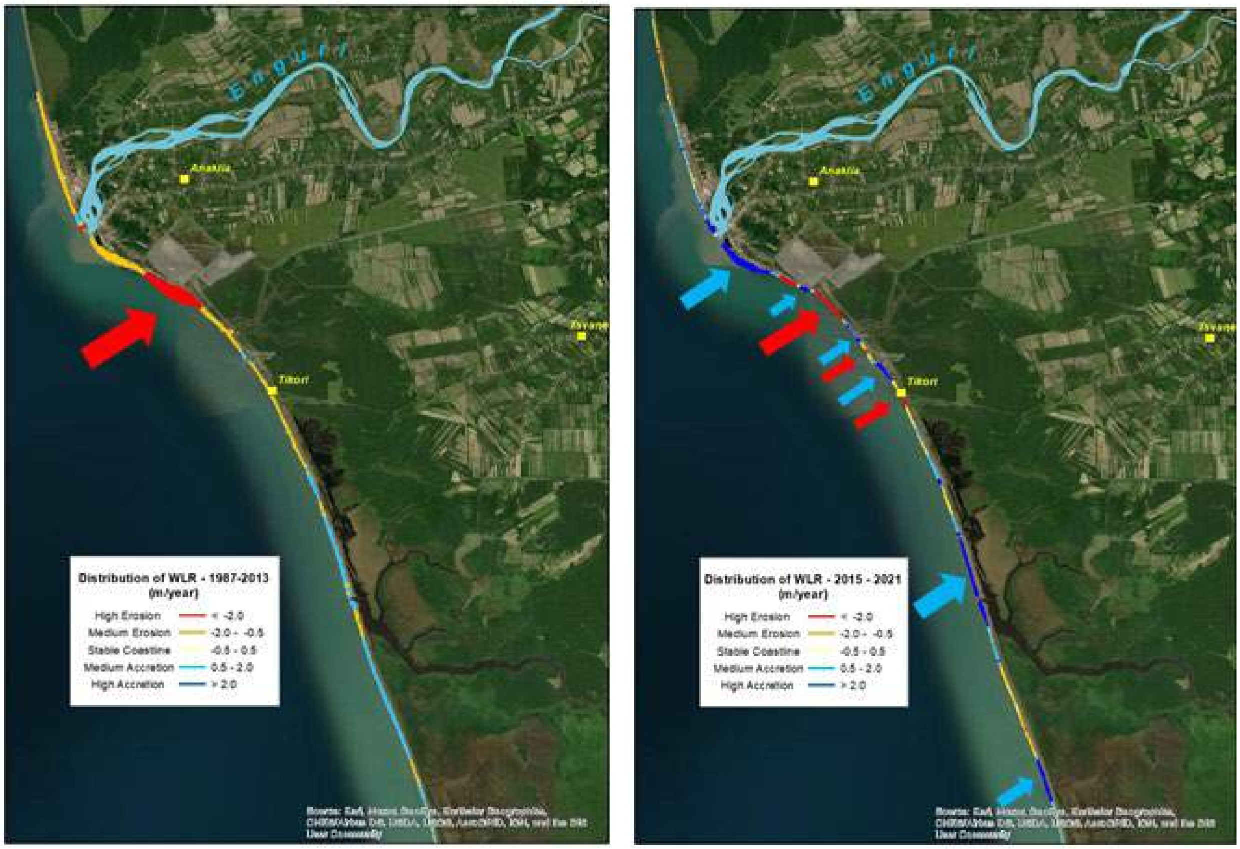


Fig 5. Significant erosion/accretion of Adjara, Guria, Samegrelo shoreline, left panel: 1987-2013. Erosion near the village of Anaklia: WLR max. (-8.4± 0.4 m/yr) NSM (-216 m). Right panel: 2015-2021. Erosion near the village of Anaklia: WLR Mak. (-8.4 ± 0.4 m/year), NSM (-48 m); the entire shoreline to the south from the Enguri River undergoes intensive change.

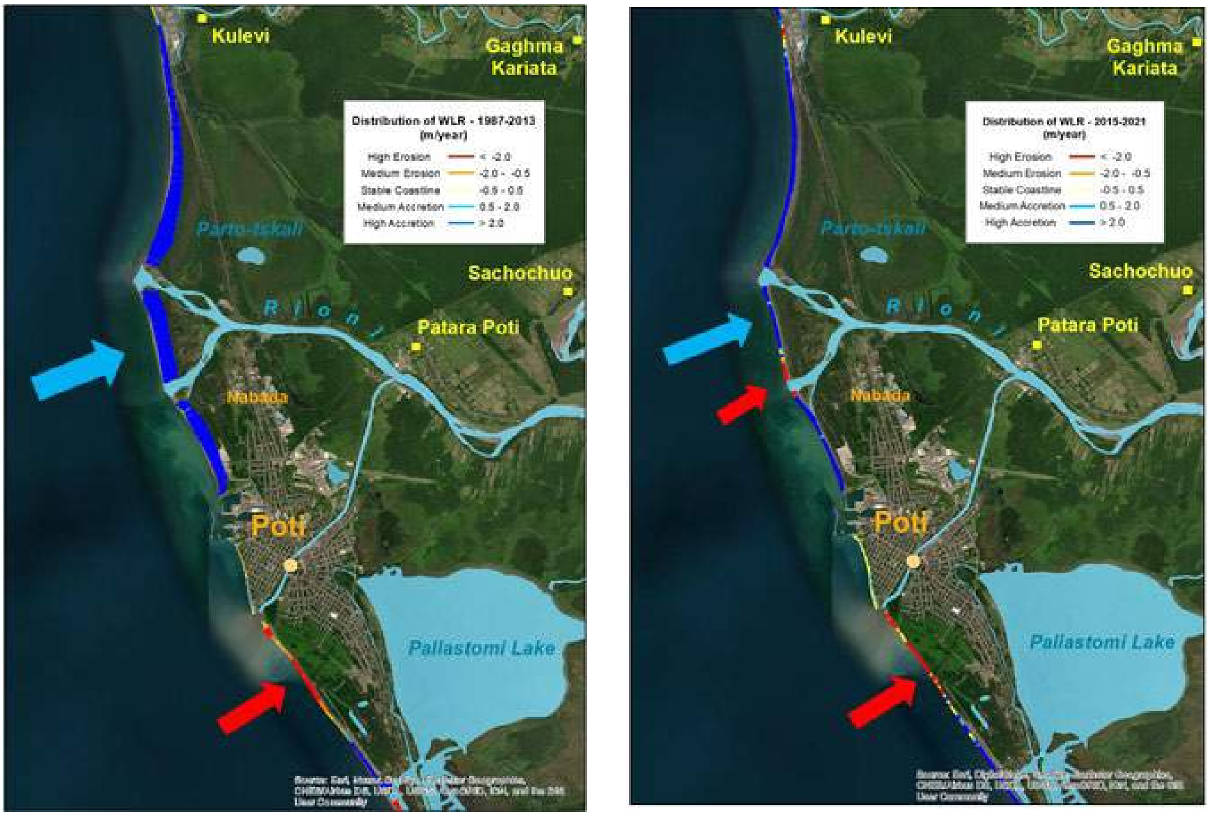


Fig. 6. Left panel: significant erosion/accretion of Adjara, Guria, Samegrelo shoreline, left panel: 1987-2013. Erosion of the Rioni river delta: WLR avrg. (11 ± 0.4 m/yr), NSM (475 m); Erosion to the south of Rioni canal: WLR Avrg. (-3 ± 0.4 m/year), NSM (-146 m). Right panel: 2015-2021. Rioni delta accretion: WLR Avrg. (7 ± 0.4m/yr), NSM (90m). Erosion at the southern branch of the Rioni delta estuary: WLR average (-6.9 ± 0.4 m/yr), NSM (-107 m); Erosion to the south of the Rioni Canal: WLR Avg. (-3 ± 0.4 m/yr), NSM (38 m).

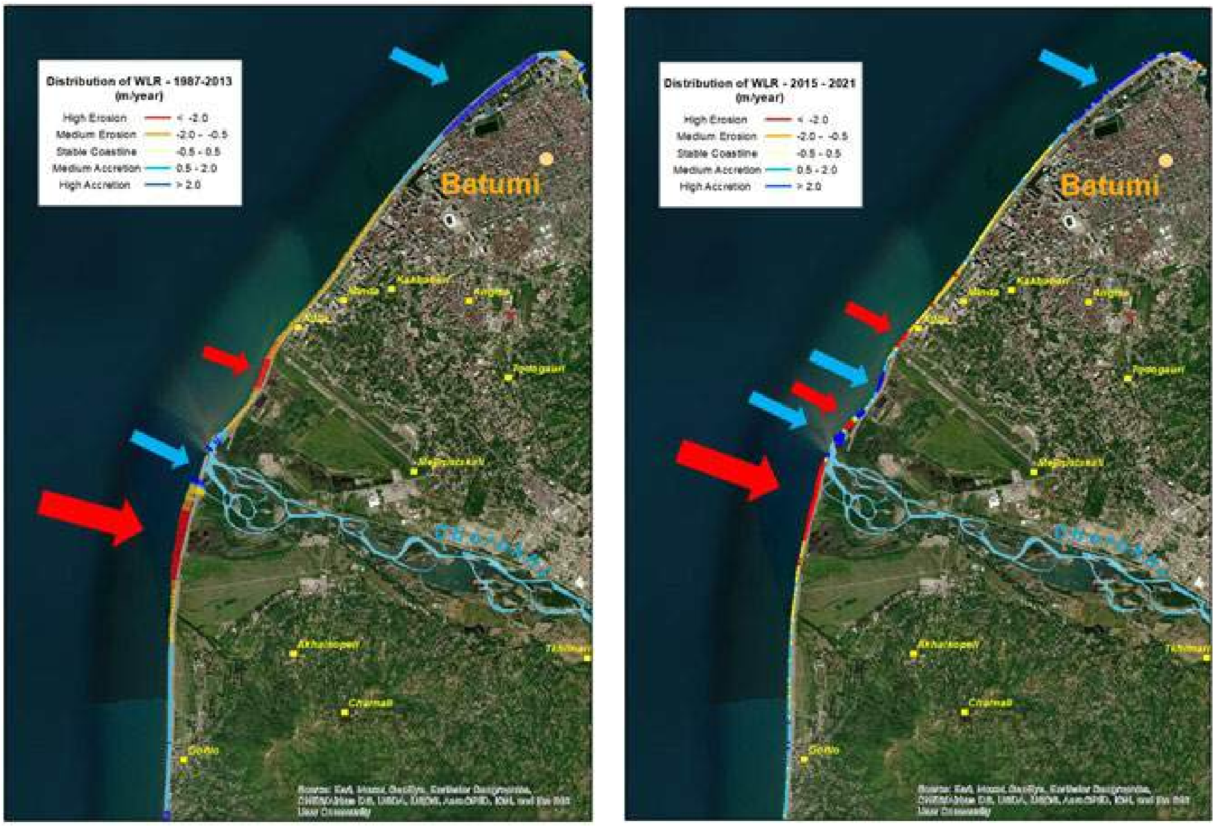


Fig. 7. Left panel: significant erosion/accretion of Adjara, Guria, Samegrelo shoreline, left panel: 1987-2013. Erosion to the south of the Chorokhi river estuary: NSM (-118 m), WLR avrg. (-3.2 ± 0.4 m/yr). Accretion to the south of the Chorokhi estuary: WLR avrg. (11 ± 0.4 m/yr), NSM (180 m). Accretion to the north of the estuary: WLR avrg. (2.5 ± 0.4 m/yr), NSM (124.5 m). Erosion of the Adlia village shoreline: WLR avg. (-2.8 ± 0.4 m/yr), NSM (-90 m). Batumi beach accretion: WLR avrg.(2.7 ± 0.4 m/yr),NSM (90 m). Right panel: 2015-2021. Accretion to the south of the Chorokhi River estuary:WLR avrg.(3.5 ± 0.4 m/yr),NSM (27 m), accretion to the north of the estuary: WLR avrg.(16.2 ± 0.4 m/y),NSM (151 m); alternating accretion/erosion towards Adlia; Erosion of the shoreline of Adlia: WLR avrg.(-3.2 ± 0.4 m/y),NSM (-22 m). Erosion to the south of Chorokhi river estuary: WLR avg.(-5.2 ± 0.4 m/y),NSM (-43 m); Batumi beach accretion: WLR avrg.(2.5 ± 0.4 m/y), NSM (27.5 m).

Fig.8, 9. Gravel Mining in Rioni River Basin.

Fig. 9. Gravel Mining in Chorokhi River Delta

Fig. 10. Sand and Gravel Mining in PONTOS GE Pilot Area

Fig. 11. Vartsikhe HPP, Rioni River

Fig. 12. Black Sea Coast, accretion

Fig. 13. Black Sea Coast, erosion

October 2021

September 2022

Fig. 14. Erosion of the Black Sea coast near city Poti.

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