Coastal dynamics of the Gulf of Kalamita (Western Crimea)

I V Agarkova-Lyakh
Institute of natural and technical systems, Sevastopol, 299011, Russia
E-mail: iva_crimea@mail.ru

Abstract. The performed research showed that since the first third of the 20th century until today the beach width at various sections of the Gulf of Kalamita has decreased two- to fourfold, and at some of them beaches have totally disappeared. The average coast erosion rate for the last 100 years has been 1.3 m/yr, with the maximum being 7.8 m/yr. These processes are accompanied with depletion of debris on the beach and underwater slope, erosion of bench deposits, and destruction of coastal structures. This is due to deficiency of beach-forming material resulted from intense economic management in the coastal area. Implementation of scientifically and technically sound coastal protection projects is essential to preserve the beaches of the Gulf of Kalamita.

1. Introduction
Beaches of the Gulf of Kalamita are the main recreational resource and tourist attraction in the Western Crimea. From the 1930s, the beach width in some sections of the bay began to decrease gradually followed by almost complete degradation in the 1980s. Now, these processes are a serious regional problem, the main cause being active economic management in the coastal area, the scale of which on the world ocean shores is increasing [1, 2].

The paper describes the beach and coastal dynamics of the Gulf of Kalamita based on long-term observations of the 20th to early 21st cc.

2. Methods and results
The paper uses file materials from the leading research organizations of Crimea [3-8] and results of our own field research for 1998–2017. The main information processing methods were comparative-geographical, comparative-historical and cartographic ones. During the fieldwork, we used methods of beach and coast observation at key locations, instrumental and semi-instrumental measurements of coast and beach morphometric features, and collection of photographic evidence of the coastal situation. The key monitoring area was the section of the Sakskaya Bay-Bar coast between G. Titov Zvezdnaya Children's Recreation Camp (CRC) and the village of Pribrezhnoye.

The Gulf of Kalamita is situated off the western coast of Crimea and is bounded by the Cape Evpatoriyskiy in the north and the Cape Lukull in the south (figure 1). The total length of the gulf's shores is about 66 km (according to a 1:200 000 scale map). Previously, the gulf coasts were an example of an erosive-accumulative pair consisting of two different genesis areas: the northern accumulative (from the Cape Evpatoriyskiy to Lake Kyzyl-Yar) and the southern erosion (from Krasnaya Gorka to the Cape Lukull) ones merged by a material exchange into a single lithodynamic system.
The beaches of the southern erosive section are formed due to sediment runoff material of the Zapadniy Bulganak and Alma rivers, products of coast and underwater slope erosion, biogenic emissions and longshore drift material (figure 1). The beaches are attached to coast slopes and composed of sandy, boulder-sandy and gravel-pebble sediments.

The beaches of the northern accumulative section are formed mainly by longshore drift material transported from the south. The longshore drift is directed from the mouth of the Belbek River to Evpatoriya and includes sediment runoff material of the Kacha and Belbek rivers, material received from the bottom, coast and bench erosion products (figure 1). These beaches are classified as full-profile (free) beaches comprising sandy, gravel-sandy and gravel fractions.

Further, let us consider changes in the beach widths at various sections of the Gulf of Kalamita in the 20th to early 21st cc. from the Cape Lukull to the Cape Evpatoriyskiy.

In the mid-1980s, there was a natural beach 8.0–10.0 m wide at the mouth of the Alma River and an artificial beach of the same width near the village of Peschanoye [8]. The beach shrinkage observed back then led to construction of coastal protection structures. Consequently, by the 1990s, there appeared 15 groins 50.0–85.0 m and long standing 50.0–500.0 m apart [10]. The space between the groins was filled with rock debris. The cliff to the north of the groin group was cut and terraced. By 1994, a nearly 850-meter long breakwater seafront was built. The constructed complex did not exist for long. In 2005, the coastal protection structures on the beaches of the village council were partially or completely destroyed.

In the mid-1980s, the beaches north of Peschanoye and near Beregovoye were 5.0 to 8.0 m wide and north of Beregovoye they were 10.0 to 15.0 m wide [8]. At that time, a sloping terraced breakwater seafront was constructed at the mouth of the Zapadniy Bulganak River (Beregovoye) [10]. In 20 years, the distance from the cliff edge to the nearest recreation buildings in Beregovoye was only 2.5 to 5.0 m [8]. The restoration of the coastal protection structures in Beregovoye, which began in 2013, has not been completed yet [10].

Near the urban-type settlement of Nikolaevka, a critical situation of beach degradation arose in the late 1970s threatening the functioning of a number of recreational facilities. In response to this, in 1981–1982, construction of a sloping terraced waterbreak seafront started in the southern and northern parts of Nikolaevka. The seafront occupying 1.5 km of the coastline was finished by 1990.

In the southern part of Nikolaevka, in the mid-1980s, the beach was about 30.0 m wide [8]. In ten years after the seafront construction, the beaches shrank dramatically, and somewhere they disappeared completely. In 2005, the sloping terraced seafront footing was eroded and concrete slabs collapsed. During 2006–2008, six transverse groins were built in this area to form artificial beaches and protect the remaining seafront [11]. This resulted in an increase of beach widths south of the groins and their rapid degradation to the north accompanied by destruction of the coastal protection structures.
In the 1990s, in the centre of Nikolaevka, the width of the beach protected by the sloping terraced seafront was 23.0–34.0 m. By 2005, it had decreased to 10.0–18.0 m near the lifeguard station [8].

To the north of Nikolaevka, in the late 1970s through mid-1980s, there was an unstable 10-meter wide beach. The beach got stable only after construction of two groins on the cape near the settlement in 1992. As a result, since the late 1990s, at the northern section in front of the cape, beach material was accumulating. At a distance of about 1.5 km south of the cape, the beach width was 25.0–35.0 m; further to the south, that was 18.0–20.0 m. As of 2005, this section generally remained stable, with the beach width being 22.0–30.0 m and its seasonal variation ranging within 5.0–7.0 m [8].

In the mid-1980s, to the south of the Bogaily Lake bay-bar, the beach was 18.0 m wide. Between Bogayly and Kyzyl-Yar lakes, the beach width was 7.0–12.0 m, and near Krasnaya Gorka it was 10.0 m. In the same years, the width of the southern Kyzyl-Yar bay-bar was 200.0 m. After construction of a hydraulic structure on the northern bay-bar in 1979–1982, the beach in front of it started accumulating at an average rate of 7.5 m/year [12]. In the early 2000s, the southern Kyzyl-Yar bay-bar shrank 1.5 times, and the coastline of its northern part protruded into the sea by 120.0 m, to the length of the hydraulic structure.

Similar processes were observed on the Sakskaya Bay-Bar. According to our research, in the early 1980s, near Titov Zvezdny CRC, there were beaches up to 60.0 m wide, of which today there are only sheer fragments left of 15.0–20.0 m width. The scarp forming here has a height of 0.1 to 1.0 m and is constantly shifting towards the land. The beach in the northern part of the Sakskaya Bay-Bar is relatively stable. In the mid-1980s, the width of various parts of the beach ranged within –3.0 to +5.0 m. During the study period, the width of the beaches in the northern part of the Sakskaya Bay-Bar remained almost unchanged and exceeded 50.0 m.

On the Lake Sasyk-Sivash bay-bar, the average beach width in the mid-1980s ranged within 30.0–50.0 m. During this period, maximum values of 50.0–100.0 m were observed for the full-profile (free) beaches opposite Pribrezhnaya, where the coastline changes its direction and longshore drift material accumulates.

On the northern Sasyk-Sivash Bay-Bar, the coastal curve turns to the west to form the Evpatoriyskaya Bay, which extends to the Cape Karantinniy.

In the late 1950s and early 1980s, the width of the Evpatoriya’s beaches at the eastern outskirts of the city in the area of Simferopolskaya Street was 30.0–50.0 m. After this territory had been flooded during a storm in November 1981, the sea began to destroy a part of this street together with the seafront. Today, attempts of individual owners to protect their houses from destruction have led to formation of rubbles of shell stones, broken stairs, concrete slabs, etc. in the seaside area.

In 1968–1972, Tereshkova Seafront was built in the historic district of the city. The seafront was a 1.8 km long concrete wall with a shaped breakwater and protruded for 30.0–50.0 m into the sea. After this reconstruction, the beaches have totally disappeared there [11].

Until the 1950s, at the Cape Karantinniy and adjacent areas, there was a broad full-profile (free) beach narrowing to 10.0–20.0 m to the east. In the late 1970s, at the Cape Karantinniy, a 200.0 m long mole of the Evpatoriya Commercial Seaport was built, whereafter a wide bank formed on the cape's east side, and on its west side (area of Gorkiy Seafront), the coast began to retreat intensely. This construction resulted in the loss of up to 50.0 m of the city's beach width [11]. After the mole erection, the beaches between the Capes Karantinniy and Yevpatoriyskiy have been constantly degrading.

In the early 20th c., the beach width at the today's M. Gorkiy Seafront was 21.0–85.0 m, but in 2005, it was only 15.0–35.0 m. Further west, at the today's Frunze Park through Zolotov Bereg Resort, the beach width was 50.0–80.0 m in the early 20th c., 30.0–40.0 m in the mid-1980s, and in 2005, it was only 6.0–15.0 m. Over 90 years, between 1915 and 2006, the beach width in the today's Orlyonok Resort House area decreased more than twofold [8]. According to estimations [11], there are no beaches within a three-kilometer zone in the central part of Evpatoriya; within another 1.5-kilometer section of the coastal area, they have significantly shrunk.
The width of the Moynaki Lake bay-bar decreased from 125.0–150.0 m in 1989 to 90.0–100.0 m in 2005. Intense erosion and coastline retreat are supported by erosion scarps up to 0.8 m high. On some beaches, the sediments are almost completely washed away and the bedrock loam soils are exposed.

Publications concerning sediment deposits on the beaches of the Gulf of Kalamita in the late 1980s indicate that their largest amounts were concentrated on accumulative bay-bars of saltwater lakes and in the zone of longshore drift discharge (apex of the gulf) [7]. Their average specific volume was increasing from south to north (figure 2). Thus, in the southern part of the gulf, between Peschanoye and Nikolaevka, the average specific volume of beach sediments was 7.4–12.0 m$^3$/m increasing to 33.9–42.0 m$^3$/m towards the Lake Bogaily bay-bar and the settlement of Novofedorovka. At the Sasyk-Sivash bay-bar, the average specific volume of sediments reached its maximum of 85.0 m$^3$/m. On the Evpatoriya beaches, the sediment amount decreased by a factor of 3 to 5, varying from 17.6 m$^3$/m near the Cape Karantinniy to 28.0 m$^3$/m near the Cape Evpatoriyskiy [7]. The comparison of variation coefficients between the two coastal areas had shown that the beaches of the Cape Karantinniy and Nikolaevka (36.4 % and 25.7 %, respectively) were the most dynamic while the beach at the Sasyk-Sivash Bay-Bar was the most stable. Five out of seven testing areas showed an insignificant average annual decrease of the beach width: from 0.7 to 3.6 m (figure 2).

![Figure 2. Quantitative indicators of coastal zone dynamics.](image)

Thus, it should be stated that since the 1980s until now, the width of beaches in the Gulf of Kalamita has been dramatically decreasing along their entire length from the Cape Lukull to Evpatoriya, except in stable sections and areas of hydroengineering construction with a disturbed natural lithodynamical regime. As a result, the average beach width of 10.0–15.0 m is extremely insufficient to dampen the energy of sea waves causing their coasts to erode and retreat.
Today, erosion is the dominant coastal process and the main source of debris material. According to the data [8], over the last 100 years, the erosion average rate in the Gulf of Kalamita has been 1.3 m/yr, with a maximum of 7.8 m/yr. The rate of retreat varies from year to year and in the seasonal cycle it is associated with the period from November to March when the wind wave activity increases.

An objective assessment of the gulf’s coast erosion rates requires comparing the long-term observation series presented in the table. The highest erosion rates are noted at the southern erosion section. At the accumulative section, they are two or more times lower.

| Coast section                           | Observation period | Average retreat rate, m/yr | Source |
|----------------------------------------|--------------------|----------------------------|--------|
| Evpatoriya                             | 1970s              | 3.75                       | [13]   |
|                                        | no data            | 1.0–2.0                    | [8]    |
| Southern Sakska Bay-Bar                | 1941–1963          | 2.1                        | [6]    |
| Saky section                           | 1970s              | 1.0                        | [13]   |
| Sakskaya Bay-Bar                       | 1979–1982          | 2.6                        | [4]    |
| Sakskaya Bay-Bar near G. Titov         | 1983–2005          | 1.5–2.0;                   | [9, 12]|
| Zvezdny CRC                            | 3.76 (maximal)     |                            |        |
| Southern Kyzyl-Yar Lake bay-bar        | no data            | 5.0                        | [7]    |
| Krasnaya Gorka section                 | no data            | 2.0–2.8                    | [7]    |
| Northern bay-bar Bogaily Lake          | 1994–2005          | 1.36                       | [8]    |
| Southern bay-bar Bogaily Lake          | no data            | 5.0                        | [7]    |
| Section between Nikolaevka and Kyzyl-Yar Lake | 1940–1973 | 1.46                        | [6]    |
| Alma River mouth, near Peschanoye and Beregovoye | 1976–1982 | from 0.6–1.0 to 6.0        | [3]    |
| Between the Cape Lukull and the end of the bay-bar Bogaily Lake | 1976–1982 | 3.0                         | [3]    |
| Entire gulf                            | 1905–2005          | 1.3; 7.8 (maximal)         | [8]    |

As the coastline retreats, erosion of the seabed and sediments occurs on the underwater slope. Its rate decreases from the south to north of the gulf: from 0.23–0.26 m/yr to 0.02 m/yr [7] (figure 2). Only at the bottom near the Capes Karantinniy and Evpatoriyskiy, there is low accumulation with the rates of 0.06 and 0.13 m/yr, respectively, associated with the interception of the material near the Evpatoriya Seaport breakwater and discharge of longshore drifts.

The current coastal conditions in the Gulf of Kalamita are attributable to an extremely low amount of incoming debris material. With the dramatic reduction of the sediment runoff and low shell production, the main source of beach-forming material in the coastal zone is erosion of coastal slopes and the underwater slope, which have a specific volume of 2.7 m³/m-yr and 1.7 m³/m-yr of sediments, respectively [14]. Altogether, they yield about 4.4 m³/m-yr sediments on average over a long-term period but are not sufficient to completely saturate the Kalamita longshore drift. The unsaturated flow of sediment, which is formed here, with a capacity of 65.0 thous. m³/yr discharges completely to the bottom of the Evpatoriyskaya Bay leaving the beaches of the northern Gulf of Kalamita without any refeeding.

As a result, the lack of material in the coastal zone is offset by reduction of beaches and coastline retreat, erosion of the bottom, and sediments of the underwater slope. The current deficit of sediments is caused by intense economic activities in the coastal zone, as discussed in [6, 12]. The problem of the beach shrinkage and coastal retreat can be solved by implementing a system of coastal protection measures.
3. Conclusion
The formerly accumulative coasts of the Gulf of Kalamita are now actively retreating along almost their entire length, excluding areas of hydrotechnical construction with a disrupted lithodynamic regime. According to observations since the beginning of the 20th c., the width of the beaches at various sections has decreased by a factor of 2–4; the average erosion rate has been 1.3 m/yr.

Today, the main source of beach-forming material is the products of the coastline and underwater slope erosion, but their amounts are insufficient to saturate the Kalamita longshore drift completely. This situation is due to a drastic decrease in volume of the debris material reaching the coastal zone because of an increasing pressure of economic activity there. Implementation of scientifically and technologically sound coastal protection projects is essential to preserve the beaches of the Gulf of Kalamita.

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