DOI 10.59887/2073-6673.2025.18(2)-4
EDN GNHCOB

УДК 627.52

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Hybrid Modeling of Changes in the Gelendzhik Bay Coastline due to the Construction of a Marina

Received 07.04.2025, Revised 18.05.2025, Accepted 30.05.2025

Abstract

The article examines the impact of the construction of a marina on the lithodynamic processes in Gelendzhik Bay, a closed water area with a complex sediment balance. Historically, the bay was a closed system, but active hydraulic engineering (artificial beaches, port facilities) disrupted the natural morphodynamics. An integrated approach combining numerical (SWAN, Wave Watch III models) and physical modeling on a scale of 1:100 has been applied to assess the effects of anthropogenic impact.

Physical modeling has shown that the port facilities form local erosion zones./sediment accumulation. The results of experimental studies qualitatively confirm the conclusions of numerical modeling. Despite the local changes, the port does not significantly affect the overall sediment transport. The study highlights the need for an integrated approach to modeling lithodynamic processes.

Keywords: the Black Sea, Gelendzhik Bay, numerical modeling, physical modeling, experimental research, lithodynamic processes

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Гибридное моделирование изменений участка береговой линии Геленджикской бухты в связи со строительством яхтенного порта

Статья поступила в редакцию 07.04.2025, после доработки 18.05.2025, принята в печать 30.05.2025

Аннотация

В статье исследуется влияние строительства яхтенного порта на литодинамические процессы в Геленджикской бухте — закрытой акватории со сложным балансом наносов. Исторически бухта представляла собой замкнутую систему, однако активное гидротехническое строительство (искусственные пляжи, портовые сооружения) нарушило естественную морфодинамику. Для оценки последствий антропогенного воздействия применен комплексный подход, сочетающий численное (модели SWAN, Wave Watch III) и физическое моделирование в масштабе 1:100.

Физическое моделирование показало, что сооружения порта формируют локальные зоны эрозии/аккумуляции наносов. Результаты экспериментальных исследований качественно подтверждают выводы численного моделирования. Несмотря на локальные изменения, порт не оказывает существенного влияния на общий транспорт наносов. Исследование подчеркивает необходимость комплексного подхода к моделированию литодинамических процессов.

Ключевые слова: Черное море, Геленджикская бухта, численное моделирование, физическое моделирование, экспериментальные исследования, литодинамические процессы.

Ссылка для цитирования: *Аншаков А.С.* Гибридное моделирование изменений участка береговой линии Геленджикской бухты в связи со строительством яхтенного порта // Фундаментальная и прикладная гидрофизика. 2025. Т. 18, № 2. С. 58–67. https://doi.org/10.59887/2073-6673.2025.18(2)-4 EDN GNHCOB

For citation: *Anshakov A.S.* Hybrid Modeling of Changes in the Gelendzhik Bay Coastline due to the Construction of a Marina. *Fundamental and Applied Hydrophysics*. 2025;18(2):58–67. https://doi.org/10.59887/2073-6673.2025.18(2)-4

1. Introduction

The construction of yacht ports and other hydraulic structures in the coastal zone inevitably leads to the transformation of natural processes, including changes in sediment transport, flow patterns and the reshaping of the coastline [1–6]. These issues become particularly relevant in conditions of limited bays, such as Gelendzhik, where anthropogenic impact can disrupt the delicate balance between abrasion and accumulation. In recent decades, the active development of the resort region's infrastructure has led to the need to predict and minimize the negative effects of construction on the coastal zone.

Gelendzhik Bay, bounded by the Tonkyy and Tolstyy capes, is a unique natural and anthropogenic complex [7,8]. Historically, the lithodynamic system of the bay is a closed cell where the beach-forming material does not extend beyond the capes. However, intensive economic activity has radically changed the natural processes of morphodynamics.

The anthropogenic transformation of the coastal zone began in the 1970s with the creation of an artificial sandy beach in the eastern part of the bay, which was repeatedly replenished with additional deposits. In the 1990s, a project was launched to create a pebble beach with a length of about 1 km between Tolstyy Cape and the yacht club. In 2002, the construction of a marina port at Cape Tonkyy with a stone-filled pier further changed the hydrodynamic regime of the bay.

The current state of the coastal zone is of serious concern. The central part of the bay is practically devoid of natural beaches, the coastline is cluttered with numerous piers and retaining structures. The only significant artificial beach in the eastern part is gradually deteriorating at a rate of about 5 cm/year.

Traditional methods for assessing shoreline changes, based on field observations and analysis of historical data, often fail to account for the combined influence of hydrodynamic, morphodynamic, and anthropogenic factors. In this regard, the application of an integrated approach combining mathematical and physical modeling opens new possibilities for high-accuracy forecasting.

This article presents a hybrid modeling approach to study changes in a section of the Gelendzhik Bay shoreline caused by the construction of a yacht harbor. In previous research, numerical modeling methods were used to evaluate lithodynamic processes. Areas of intensive seabed transformation were found to correlate with the strongest currents and were located away from the yacht harbor construction site.

However, it was impossible to validate these findings with field data on wave action, currents, and longshore sediment transport due to the lack of such observations. While no wind-wave observations were conducted in the bay, wave data from a storm in February 2003, recorded by a wave buoy deployed by the Southern Branch of the Shirshov Institute of Oceanology (RAS) near Gelendzhik [10], were used in this study to calibrate the SWAN model. Current measurements in the bay were taken outside storm periods, making them unsuitable for verifying the modeled current fields in the study area. For this reason, physical modeling of lithodynamic processes in a wave basin was conducted to validate the numerical results.

Given the size of the bay, approximately 3.0 × 4.5 km, the implementation of full-size physical modeling in the conditions of the wave basin of the National Research University MSUCE would require the choice of a modeling scale of 1:250. Since the depths of the bay range from 1.0 to 10.0 m, in laboratory conditions they will range from 0.4 cm to 4.0 cm. It is almost impossible to create a physical model of the bay in laboratory conditions, at such depths, with accurate reproduction of bathymetry. Therefore, experimental studies were conducted only in the area of influence of the yacht port (Fig.1), located along the western coastline of the bay.

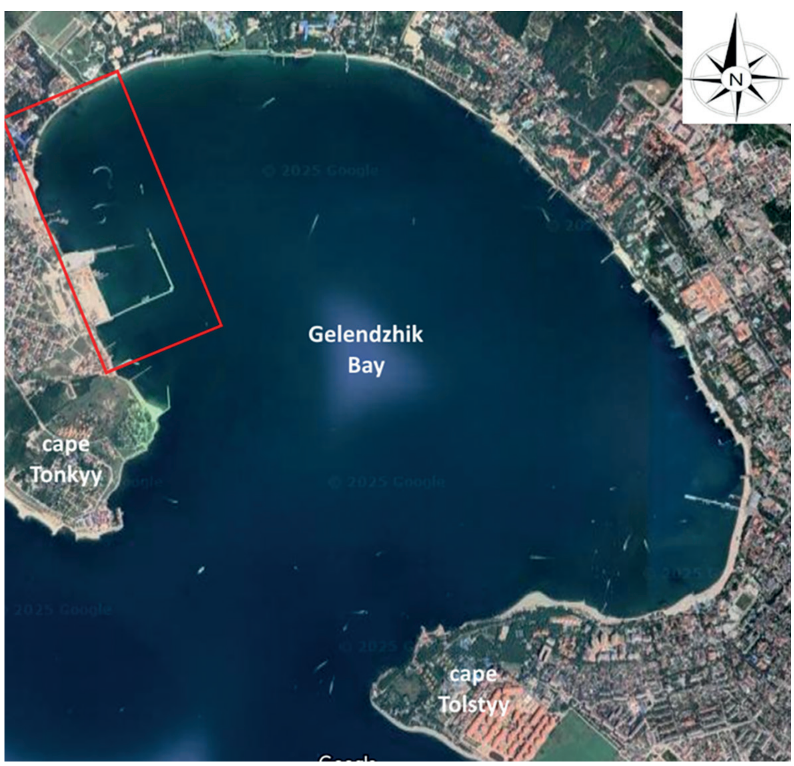

Fig. 1. The area of experimental research (shown in red)

2. Methods

To determine the parameters of an extreme storm inside Gelendzhik Bay, the SWAN and Wave Watch III models were used [11–13], the wind fields for which were calculated based on data from the NCEP/NCAR reanalysis of wind fields in the period from 1983 to 2012 [14–16]. When setting up experimental studies, it was assumed that the main seabed transformation would occur after an extreme storm.

The investigations were conducted for southeastern wave direction impacting the yacht port structures, which forms due to the refraction of southwestern storm waves at Tonkyy Cape. The parameters of the extreme storm waves were as follows: wave height $h_{13\,\%} = 2.2$ m ($h = 2.2$ cm, model data), the average period $T = 11.0$ s ($T = 1.1$ s, model data), the duration of the storm is 5 days (12 hours, model data) [17, 18].

In laboratory studies of local scour phenomena, fine sand with properties similar to natural soils is commonly employed as model sediment. The model sand is specifically selected to ensure the lowest possible critical shear velocity for particle motion. The absolute minimum values of critical velocity ($0.10 \le V_{kr} \le 0.25$ m/s) are characteristic of coarse sands with particle sizes ranging from $0.25 \le d \le 1.00$ mm (d — particle diameter).

Analysis of near-bottom velocities induced by southeastern wave action in the port's coastal zone, conducted using the second-order finite-amplitude wave theory [19], revealed that under prototype conditions, the water particle velocity (V_d) in near-bed regions (depths from 6.0 to 4.0 m) ranges from 2.1 to 3.9 m/s. Thus, the prototype near-bed water particle velocity significantly exceeds the critical sediment motion threshold (V_d/V_{kr}), indicating that the scour process can be considered self-similar according to this criterion.

Under experimental conditions, it is sufficient to maintain the condition $Vd/Vkr > 1$ for the velocities of water particles at the bottom in order to obtain a qualitative analysis of sediment movement in the coastal zone. For SE wave conditions, with a water depth of d = 4.0 cm on the model and a wave height of $h_{13\,\%} = 2.2$ cm, the bottom velocity is: $V_d = 39.0$ cm/s. Accordingly, using sand with a grain size from 0.25 to 1.0 mm on the model, it is possible to provide, without any special errors, a sufficiently high-quality experimental analysis of local washouts in the coastal zone of the port.

Two configurations of the coastline were considered: without port facilities and with port facilities. The construction of physical models was carried out on a scale of 1:100. When making the model, maximum conformity to nature was observed.

To study the movement of sediments, screeds were used, on which a vertical scale was applied, in increments of 1.0 mm (Fig. 2). During the preparation of each of the experiments, the sand layer was compacted, spilled with water and carefully leveled with an error of ± 1 mm using a laser level. The bathymetry of the bottom of the model strictly corresponded, on a given scale, to the bathymetry of the bottom of a full-scale object.

Measuring screeds were rigidly mounted on a cement screed, on top of which sandy soil was poured and tamped. The marks of the seabed were recorded before the experiment began.

After the experiment was completed and the water was drained from the pool, the surface of the bottom soil was photographed, and its changes were measured using installed screeds. The relative measurement error was about 30 %. Fig. 3 shows the preparation of the physical model for experiments.

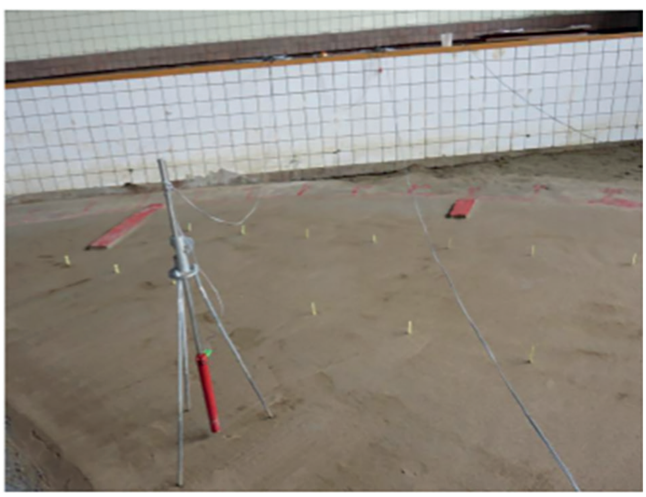

Fig. 2. Installed screeds on a physical model

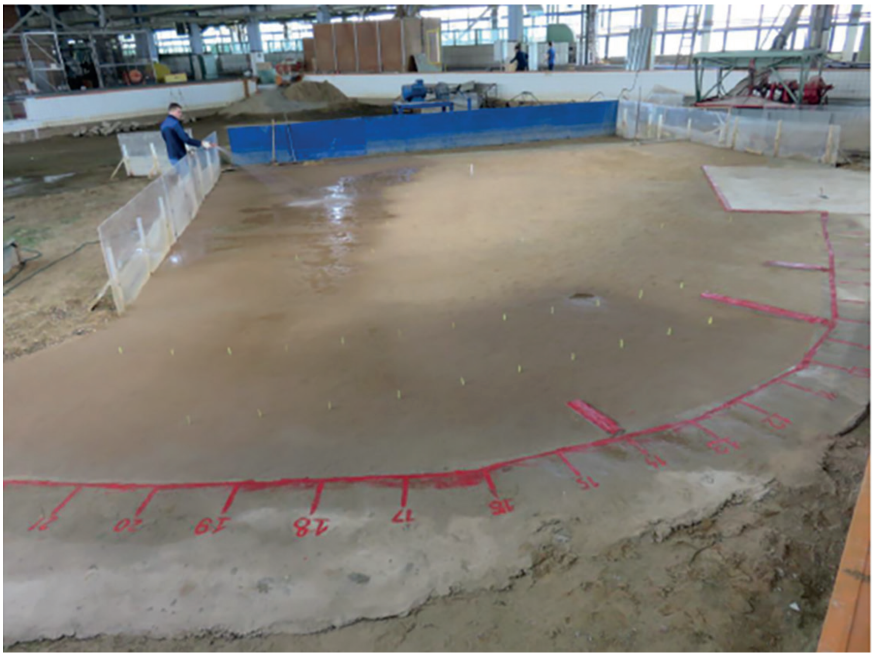

Fig. 3. Preparation of the physical model

3. Results and Discussion

Experimental studies in the wave basin are shown in Fig. 4–5. Fig. 6–7 shows the results of experimental studies: the position of the coastline and the increments of the markings measured by the screeds are shown for the configuration of the coastline without the structures of the yacht port and for the configuration with the structures of the port (with the design dredging of the water area).

The protective structures of the yacht port (points 1–4) block the sediment flow and form an accumulation zone. There is a slight increase in sediment marks in the presence of port facilities (by about 0.4 m). No significant differences in the increment of marks were found at points 4–9 located along the breakwater.

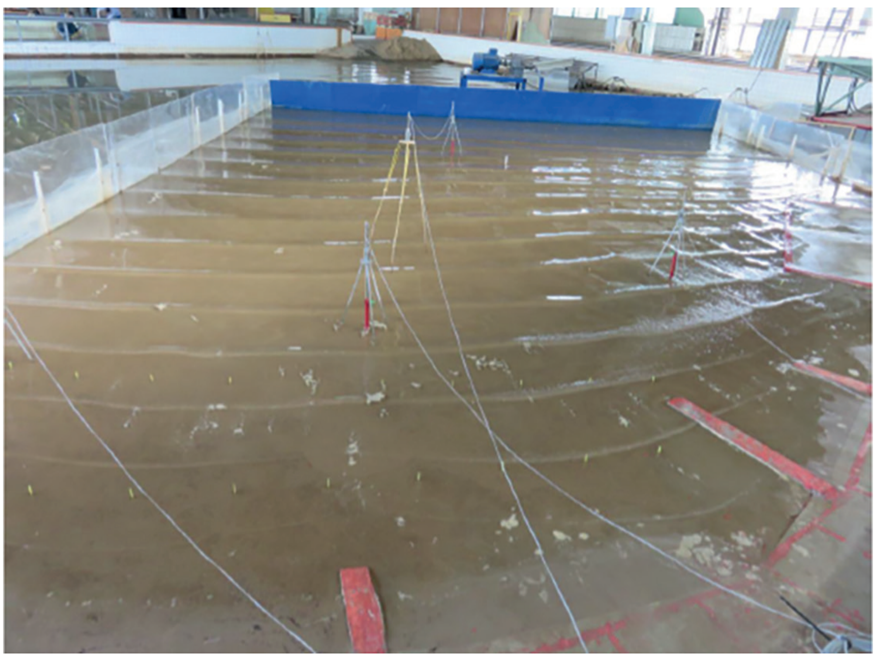

Fig. 4. Experimental studies for the configuration of the coastline without yacht port facilities

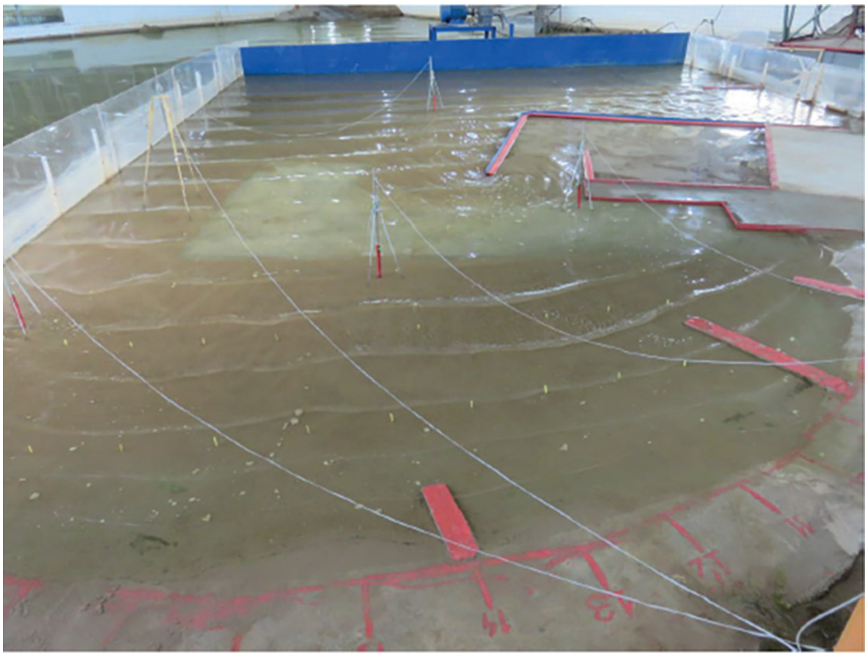

Fig. 5. Experimental studies for configuration with yacht port facilities (with design dredging of the water area)

The sedimentation process was also not detected in the dredging area of the yacht port (points 10–16).

Along the northern coastline, at a distance of up to 160.0 m (points 17–28), there is an increase in sediment marks, in the presence of protective structures. The average increment of the marks is about 0.3m. Near the coastline, at a distance of 50.0 m to 80.0 m (points 29–38), there is no influence of coastal structures on the sediment flow.

The variation in experimental values of increments of marks is largely due to the difficulties of preparing the bottom of the physical model in the basin at large scales (1:100) and shallow depths of the bay in the vicinity of the port from 2.0 m to 8.0 m (on the model from 2.0 cm to 8.0 cm).

The results of measuring the coastline behind the new port, with and without fencing structures, after the storm, are shown in Fig. 6–7. Based on the results of experimental studies, it follows that up to section 8, the impact of new port facilities on the coastline is insignificant. The presence of port facilities affects the position of the coastline after section 8 and reaches its maximum of 3.0 m for nature data (sections 21–22).

Analyzing satellite images of Gelendzhik Bay within sections 9–23, it is possible to notice the absence of beaches (Fig. 8). In these areas, the coastline is protected by coastal reinforcement in the form of concrete slabs. These details were not taken into account in the physical model, as these experimental studies are "estimates from above". The main purpose of the study is to qualitatively confirm the results of numerical studies performed in previous work [17].

The conducted experimental studies have confirmed the main conclusions obtained from the results of numerical modeling of lithodynamic processes. The port facilities do not significantly affect the overall picture of sediment movement within the port's area of influence.

4. Conclusion

The construction of hydraulic structures, such as yacht ports, in the coastal zone of Gelendzhik Bay can have a significant and multifactorial impact on natural processes, leading to a change in the hydrodynamic regime and the redistribution of sediment transport. In the conditions of the limited water area of the bay, where the natural balance between abrasion and accumulation is extremely vulnerable, anthropogenic activity becomes a key factor determining the evolution of the coastline.

In this paper, an integrated approach combining numerical and physical modeling is applied to assess the consequences of the construction of a yacht port. Numerical calculations performed using the SWAN and Wave Watch III models allowed us to determine the parameters of an extreme storm. However, the lack of systematic field data on waves, currents, and sediment transport required additional verification of the results using physical modeling methods.

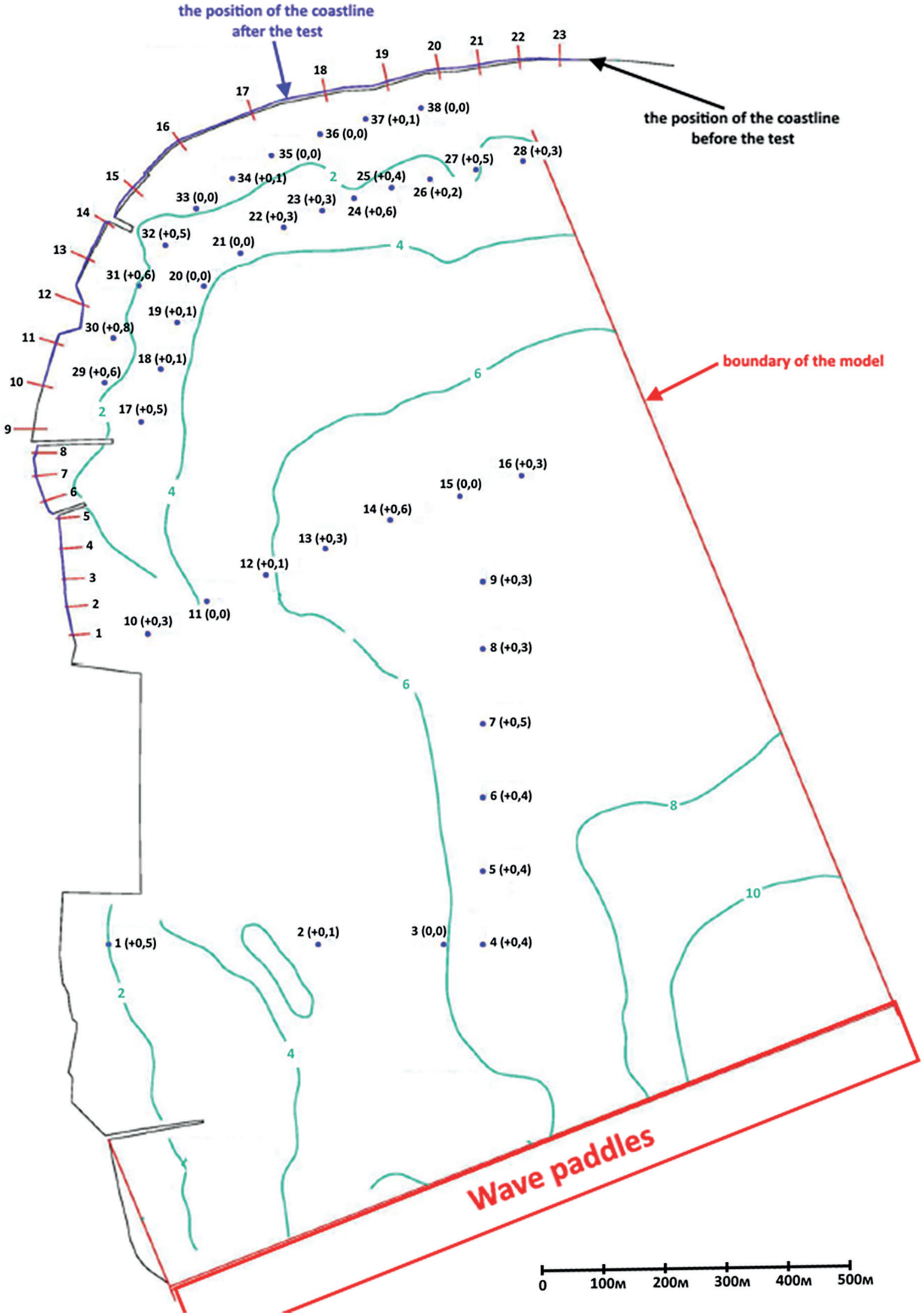

Fig. 6. The results of experimental studies for the configuration of the coastline without yacht port facilities, M 1:100. Increments of marks are indicated for nature data, m

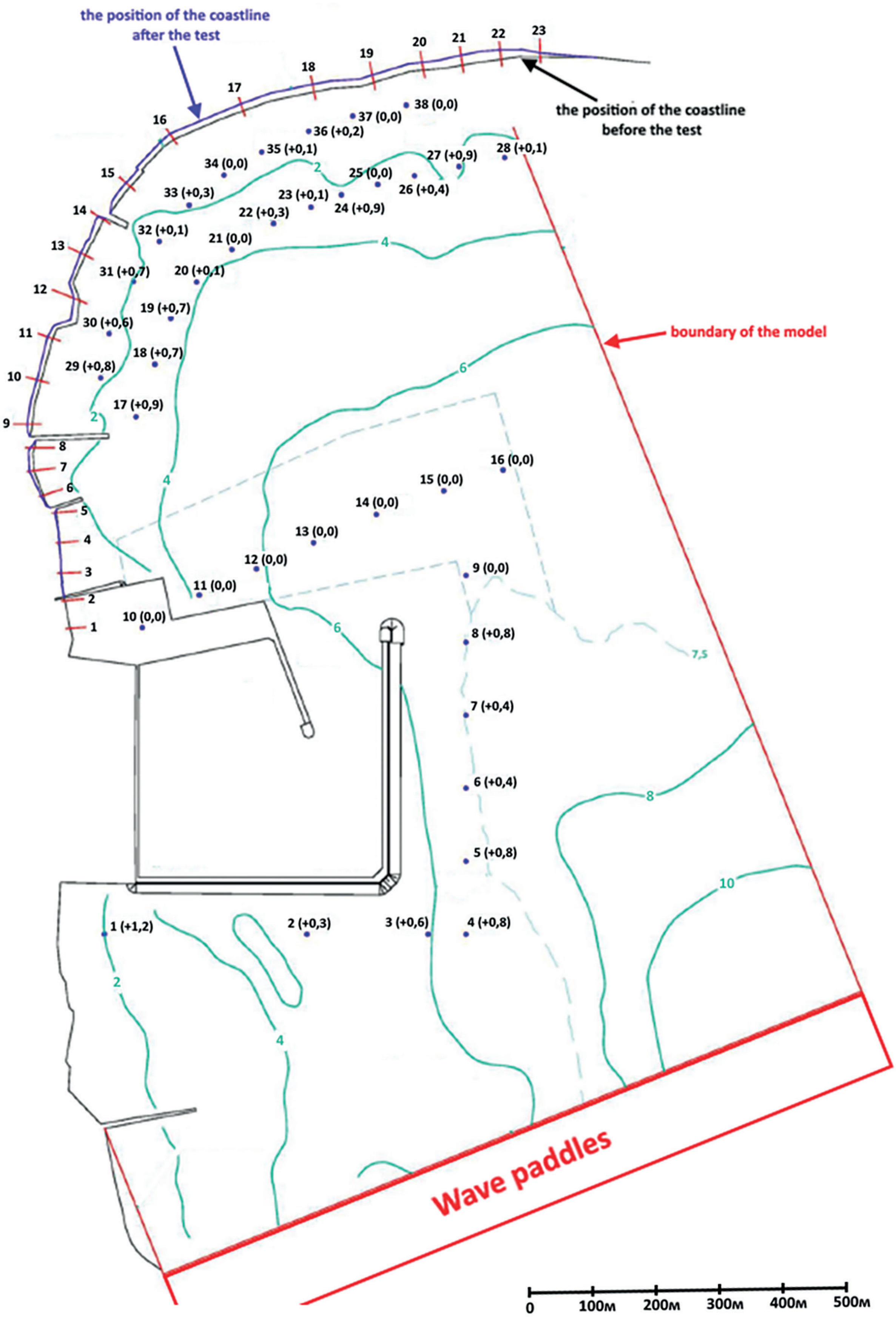

Fig. 7. The results of experimental studies for configuration with yacht port facilities (with design dredging of the water area), M 1:100. Increments of marks are indicated for nature data, m

Fig. 8. Satellite image of Gelendzhik Bay within sections 9–23

Experimental studies in the wave basin, conducted on a scale of 1:100, confirmed that the port's protective structures create a local sediment accumulation zone with increments of up to 0.4 m. At the same time, no significant changes in sedimentation were detected in the dredging zone.

It is important to note that the conducted research has revealed a number of methodological difficulties associated with the physical modeling of shallow-water zones. The measurement error was about 30 %, due to the difficulties of accurately reproducing bathymetry at shallow depths (2–8 cm on the model). Nevertheless, the results obtained allow us to conclude that the construction of a yacht port does not significantly affect the lithodynamic processes in the bay.

The conducted research demonstrates that the sustainable development of coastal territories, especially in conditions of intense recreational and economic stress, requires an integrated approach based on modern modeling methods and constant monitoring. This is the only way to ensure a balance between economic interests and the preservation of fragile coastal ecosystems.

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