ISSN 2413-5577, Ecological Safety of Coastal and Shelf Zones of Sea, 2024, No.2, pp. 60–75.

Original article

Characteristics of Storm Waves in Laspi Bay (Black Sea) Based on Results of Numerical Modeling

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Abstract
This paper studies the characteristics of storm waves in Laspi Bay (Crimean Peninsula) using the numerical hydrodynamic model SWASH with a spatial resolution of 5 m. The wave reanalysis data obtained from the spectral model SWAN were set as boundary conditions. The fields of significant wave heights and wave current velocities in the bay were analyzed for storms of various regime conditions. It was established that the maximum values in the bay could reach 2.5–3.0 m, 4.0–4.5 m, 5.0–5.5 m and 6.0–6.5 m during storms that are possible once a year, once every 5, 10 and 25 years, respectively. An increase in wave velocities to 1.5–3.0 m/s occurred near the coast at depths of less than 10 m during storms that are possible once every 25 years. The influence of the protective breakwater, built in the 1980s, on the waves was local and manifested itself in the formation of a shadow zone on its downwind side. The possible influence of storm waves on the reduction of bottom vegetation in Laspi Bay was discussed. An analysis of the wave load on the bottom of the bay showed that during periods of extreme storms in its waters, the slopes most susceptible to the effects of waves were in the depth range from 2 to 12 m where the kinetic energy density increased to 500–2000 J/m^3. At the same time, the density could reach 3000–4500 J/m^3 in the western end of the bay. The energy load values were low in the middle part of the bay. Therefore, the disappearance of bottom vegetation here could be not due to storm impact, but an increase in water turbidity caused by anthropogenic factors. The obtained results are of great practical importance for the safety of navigation, engineering and exploitation of coastal infrastructure.

Keywords: storm waves, Black Sea, Southern Coast of Crimea, Laspi Bay, numerical modeling, SWASH

Acknowledgments: The work was carried out under MHI topic no. FNNN-2021-0005 “Coastal Research”. Calculations were carried out on the MHI computing cluster.

For citation: Belokon, A.Yu. and Fomin, V.V., 2024. Characteristics of Storm Waves in Laspi Bay (Black Sea) Based on Results of Numerical Modeling. *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 60–75.

Характеристики штормового волнения в бухте Ласпи (Черное море) по результатам численного моделирования

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Аннотация
Исследуются характеристики штормового волнения в бухте Ласпи (Крымский полуостров) с использованием численной гидродинамической модели *SWASH* с пространственным разрешением 5 м. В качестве граничных условий задаются данные реанализа волнения, полученные на основе спектральной модели *SWAN*. Анализируются поля значимых высот волн h_s и скоростей волновых течений в бухте при штормах различной режимной обеспеченности. Установлено, что при штормах, возможных 1 раз в год, 1 раз в 5, 10 и 25 лет максимальные значения h_s в бухте могут достигать 2.5–3.0, 4.0–4.5, 5.0–5.5 и 6.0–6.5 м соответственно. При этом при штормах, возможных 1 раз в 25 лет, усиление волновых скоростей до 1.5–3.0 м/с происходит вблизи берега на глубинах менее 10 м. Влияние на волны защитного мола, построенного в 1980-х гг., является локальным и проявляется в формировании теневой зоны с его подветренной стороны. Обсуждаются вопросы возможного влияния штормового волнения на сокращение донной растительности в бухте Ласпи. Анализ волновой нагрузки на дно бухты показал, что в период экстремальных штормов в ее акватории наиболее подверженными воздействию волн оказываются склоны в области глубин от 2 до 12 м, где значения плотности кинетической энергии увеличиваются до 500–2000 Дж/м^3. При этом в западной оконечности бухты плотность может достигать 3000–4500 Дж/м^3. В средней части бухты значения энергетической нагрузки невелики. Поэтому к исчезновению здесь донной растительности могло привести не штормовое воздействие, а увеличение мутности воды, вызванное антропогенными факторами. Полученные результаты имеют большое практическое значение для безопасности мореплавания, проектирования и эксплуатации объектов береговой инфраструктуры.

Ключевые слова: ветровое волнение, Черное море, Южный берег Крыма, бухта Ласпи, численное моделирование, *SWASH*

Благодарности: работа выполнена в рамках темы МГИ № FNNN-2021-0005 «Прибрежные исследования». Расчеты проводились на вычислительном кластере МГИ.

Для цитирования: *Белоконь А. Ю., Фомин В. В.* Характеристики штормового волнения в бухте Ласпи (Черное море) по результатам численного моделирования // Экологическая безопасность прибрежной и шельфовой зон моря. 2024. № 2. С. 60–75. EDN PMPNVZ.

Introduction

In the last decade, many areas of the Southern Coast of Crimea (SCC) have been actively working on design, reconstruction of existing ones and construction of new coastal protection structures for the development of recreational activities. Regime and climatic information on wind waves and wave currents with high spatial resolution is necessary to carry out these works. Laspi Bay is one of such areas of the SCC.

Laspi Bay is one of the warmest areas of the SCC [1]. This is an open bay located between Cape Aya and Cape Sarych with the length of its coastline of about 4 km. The Laspi Bay area is aesthetically significant and attractive for the development of recreational activities [2].

The shores of the bay are of the abrasion and abrasion-landslide types, for which gravitational processes are well developed. The coast is formed by a fairly wide, about 20 m, pebble beach. To the west and south, small beaches alternate with piles of blocks. Low cliffs are located near the shores of the bay [1]. The underwater slope is deep, its most part is pronounced block bench, which drops steeply to a considerable depth. The central part of the bay is a sloping plain with sand and silt deposits [3]. In the coastal zone from Cape Aya to Cape Sarych, stable alongshore anticyclonic currents with velocities of up to 0.6 m/s are formed for most of the year. The hydrological regime of Laspi Bay is determined by the influence of these currents, influx of deep waters into surface layers during surge phenomena and water exchange with the open sea [4].

In 1983, as field studies showed [5], Laspi Bay was in a natural or close to natural state, in which the ecological balance of the coastal zone was maintained. The bay was characterized by an abundance of unique habitats of bottom vegetation – Cystoseira, phyllophora, eelgrass.

In the late 1980s, a hydraulic structure was built in the eastern part of Laspi Bay, which partially blocked the coastal sediment flows at its top [6]. In 2009, the *Dream Bay* hotel complex was built in the southeastern part of the bay. The construction was accompanied by large-scale coastal protection works which led to a change in the configuration of the coast and the underwater coastal slope. However, the embankment and breakwater wall of the complex were partially destroyed after the first strong storms [7]. Anthropogenic impact has led to additional influx of terrigenous material and its sedimentation in the coastal area [2]. As is known [8], the construction of hydraulic structures can lead to disruption of the hydrodynamic regime and changes in areas of abrasion and accumulation. Thus, studies in the Peter the Great Gulf (Sea of Japan) showed [8] that the construction of hydraulic structures had led to a significant reduction in bottom vegetation in the coastal zone.

The construction of a protective breakwater in Laspi Bay and the destruction of its coastal slope as a result of active coastal development could cause a disruption of the hydrodynamic regime of the bay, which, in turn, led to the erosion of pebble bench and additional influx of terrigenous material formed due to construction [2]. During the study at the bay top in 1998, silt and sandy bottom sediments were discovered starting at a depth of 3 m [6]. The bay, which in the 1980s was a model of the natural ecosystem of the Black Sea, has lost this status. A bottom natural complex devoid of vegetation has been formed in its central part [9]. Over a period of more than 30 years, the bay has undergone significant structural changes in the vegetation species composition and changes in the configuration of coastal boundaries [10]. In general, the stocks of macrophytobenthos in the bay decreased by 1.5 times, phyllophores – by 35 times and Zostera – by 4 times during this period [9].

The formation of the bottom natural topography of Laspi Bay could be influenced by both economic activity on the coast and natural factors. In terms of climate, the rise of the Black Sea level leads to an increase in depth near the coast and increases the influence of waves on it [11]. The average annual storm activity in the Black Sea increased by 10–15% for the period of 1991–2016 [12]. An extreme storm that occurred in November 2007 could also contribute to the partial destruction of the bay bottom vegetation. This assumption is supported by the fact that vegetation was completely destroyed at depths of up to 10 m during an extreme storm in the area of Karadag in 1992 [9]. Such consequences can be explained by the fact that strong bottom wave currents and intense turbulent mixing create movements in the upper layers of the bottom soil during storms and the plants rooted here are gradually washed out of it [8, 13].

Taking into account the above, this work aims at studying the wave regime of Laspi Bay and the degree of its influence on the phytocenosis of bottom vegetation. It should be noted that such studies have not been conducted to date.

The objectives of the work included obtaining and analyzing fields of wave heights and wave current velocities in Laspi Bay during storms of various regime conditions. The calculations were carried out taking into account the protective breakwater built in the late 1980s and without regard to it. The obtained wave characteristics can be used in developing recommendations for economic activities in the bay water area and assessing the influence of storm waves on the bottom vegetation phytocenosis.

Mathematical model and input data

Modeling of wave fields in the Laspi Bay waters was carried out with a two-dimensional version of the numerical wave model Simulating WAves till SHore (SWASH) [14]. The model makes it possible to carry out calculations of hydrodynamic fields in the coastal zone in a wide range of spatial and temporal scales, taking into account nonlinearity, refraction, diffraction and reflection of waves. The initial equations of the model are as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial x} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + \frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial x}dz + c_f\frac{u\sqrt{u^2+v^2}}{h} = \frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x} + \frac{\partial h\tau_{xy}}{\partial y}\right), \tag{2}$$

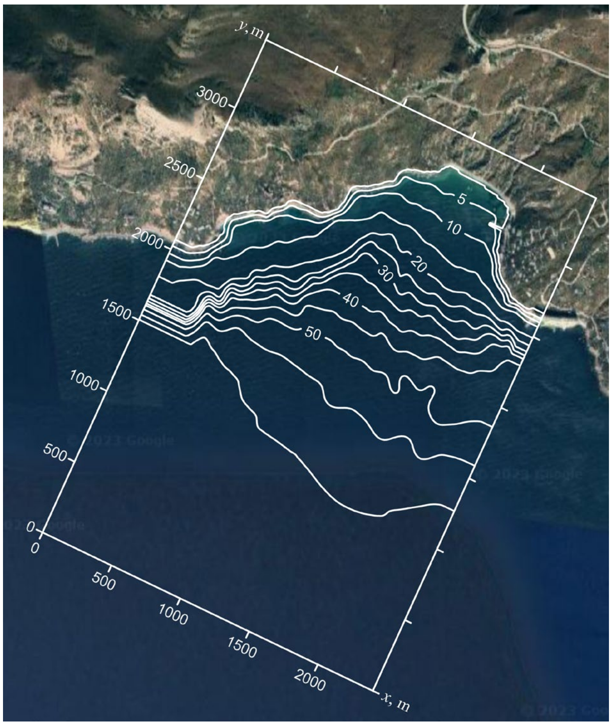
$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + \frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial y}dz + c_f\frac{v\sqrt{u^2+v^2}}{h} = \frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x} + \frac{\partial h\tau_{yy}}{\partial y}\right), \tag{3}$$

$$\tau_{xx} = 2\nu_t\frac{\partial u}{\partial x}, \qquad \tau_{xy} = \tau_{yx} = \nu_t\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right), \qquad \tau_{yy} = 2\nu_t\frac{\partial v}{\partial y}.$$

Here, t is time; x, y are Cartesian coordinates; axis z is directed upwards; $\zeta(x, y, t)$ is deviation of free surface from undisturbed level; $h = d + \zeta$ is total depth equal to the sum of free surface deviation and depth d in the undisturbed state of liquid; u and v are x and y velocity components averaged by depth; $q(x, y, z, t)$ is non-hydrostatic pressure; g is gravity acceleration; $c_f = gm^2/h^{1/3}$ is bottom friction coefficient, m is Manning's roughness coefficient; τ_{xx}, τ_{xy}, τ_{yx}, τ_{yy} are turbulent stress tensor components; ν_t is horizontal turbulent viscosity coefficient.

A rectangular computational grid of the bay water depths with a resolution of 5 m obtained on the basis of digitizing navigation charts was used for the numerical solution of system of equations (1)–(3). The dimensions of the computational domain were 3500 × 2500 m. To optimize the numerical algorithm, a coordinate system was used with the x axis directed from northwest to southeast (Fig. 1).

At the seaside boundary of the computational domain (at $y = 0$), significant wave height h_s and average wave period $\bar{\tau}$, which could occur once every n years, were specified. These parameters were obtained based on wave reanalysis data for the period 1979–2021 using the spectral model SWAN [15, 16] (Table 1).



F i g . 1 . Bottom topography of the calculation area (available at: https://www.google.com/maps/@44.3927988,33.7329232,12998m/data=!3m1!1e3?entry=ttu

Table 1. Wave parameters

T, year	$\bar{h}$, m	h_s, m	$\bar{\tau}$, s
1	3.3	5.2	9.3
5	4.1	6.5	10.1
10	4.5	7.1	10.5
25	5.0	7.9	11.1

Note: Average wave height $\bar{h}$, significant wave height h_s and average wave period $\bar{\tau}$ in the seaside of Laspi Bay at a depth of 65 m, possible once a year, once every 5, 10 and 25 years according to retrospective calculations of waves in the Black Sea for the period 1979–2021 [15, 16].

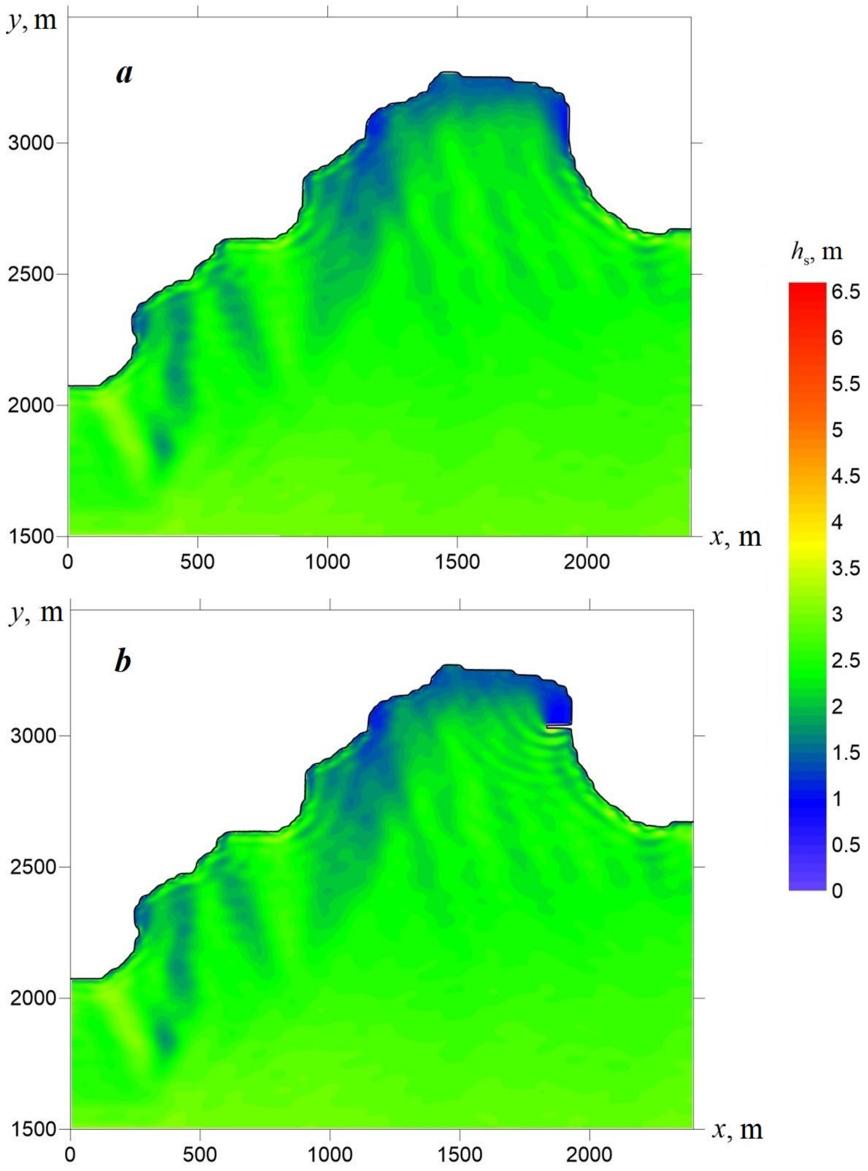
At the liquid lateral boundaries of the computational domain (at $x = 0$ and $x = 2500$ m), the radiation condition was set. The horizontal turbulent viscosity coefficient was determined using the Smagorinsky formula with constant $C = 0.2$. Manning's roughness coefficient is $m = 0.022$ s/m$^{1/3}$. The integration time step was 0.05 s.

Results of modeling and discussion

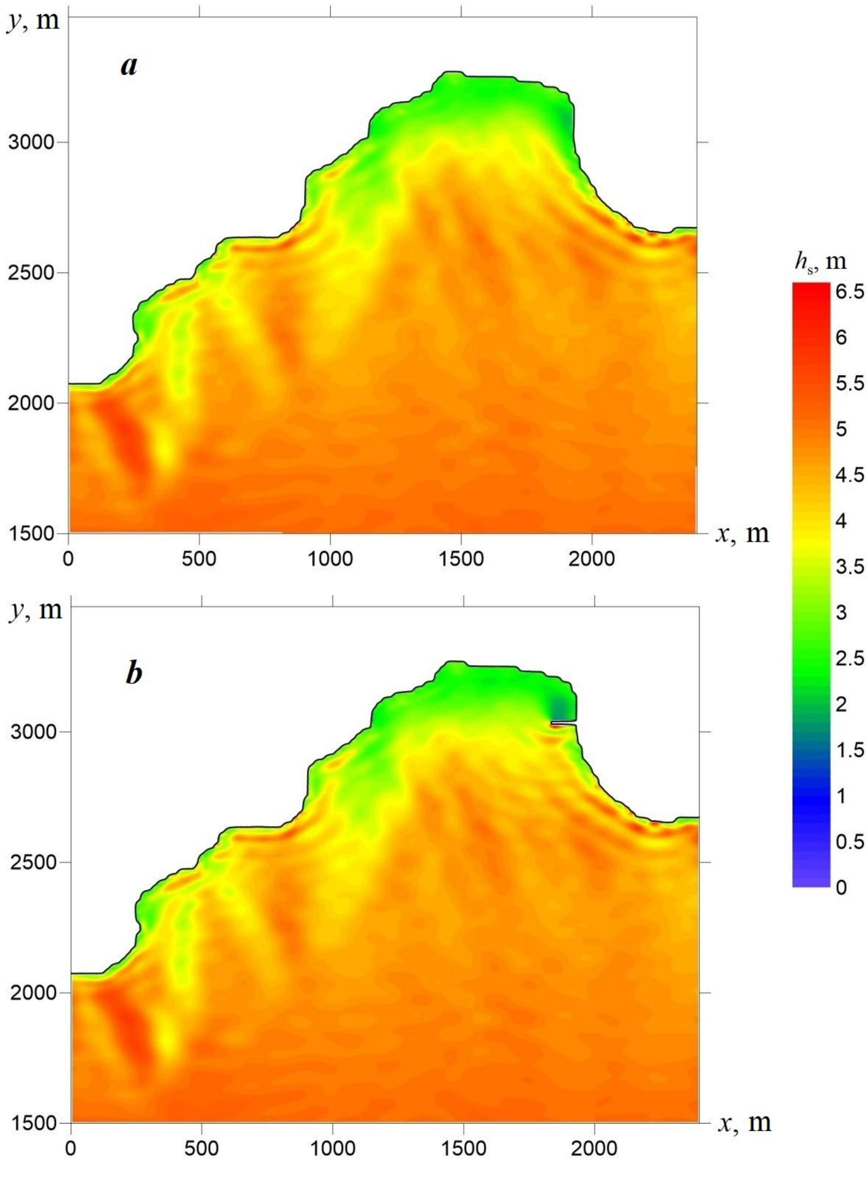
As a result of numerical experiments, significant wave heights and wave current velocities in Laspi Bay during storms of various regime conditions were obtained. Calculations were carried out taking into account the protective breakwater and without regard to it. Wave fields were constructed based on numerical modeling data averaged over 100 periods of the incoming wave (~ 20 min). In each calculation node, the significant wave height was calculated using the following formula: $h_s = 4\sqrt{D}$, where D is free surface elevation variance ζ.

As a result of the analysis of spatial structure h_s it was found that during storms possible once a year, once every 5, 10 and 25 years, significant wave heights can reach 2.5–3.0, 4.0–4.5, 5.0–5.5 and 6.0–6.5 m, respectively (Figs. 2 and 3). When comparing the calculation results obtained taking into account the protective breakwater and without regard to it, it is clear that the structure has a local influence on wave dynamics. Near the breakwater, on its downwind side, a shadow zone of about 90 × 110 m is formed. Significant wave heights in this zone were 0.9 and 1.8 m during storms possible once a year and once every 25 years, respectively. During a storm possible once a year, the waves on the downwind side of the breakwater are 3.5–4 m high. In the case of a storm possible once in 25 years, the wave heights were 4–6 m, and in the wave shadow zone the wave heights decreased to 1.5–2.0 m.

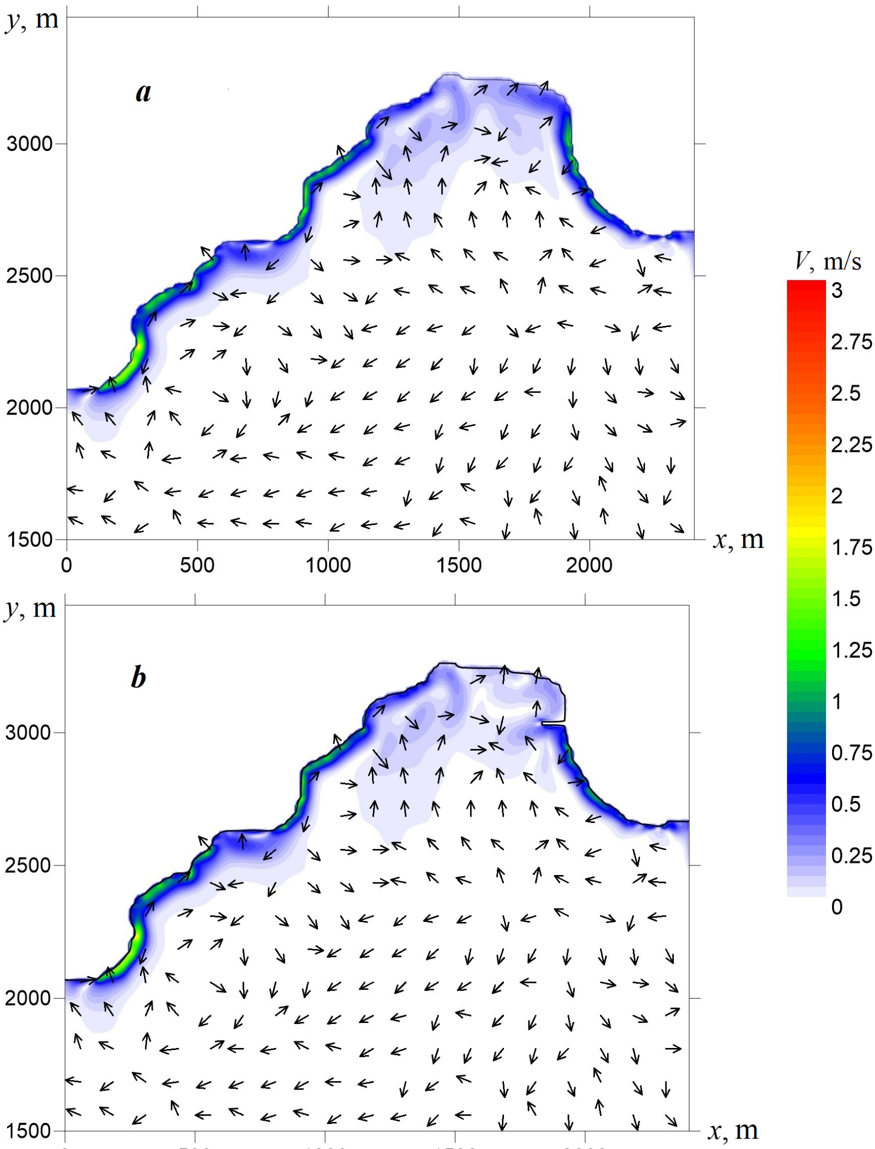
The wave current patterns during storms of various regime conditions in Laspi Bay are considered. Figs. 4 and 5 show velocity and direction of wave currents in the bay during storms possible once a year and once every 25 years. It is evident that the zones of maximum wave velocities are located along the lateral boundaries of the bay. During a storm possible once a year, the values of wave velocities were 0.5–1.5 m/s at depths of less than 10 m. During storms possible once every 25 years, the velocities can increase to 1.5–3.0 m/s in these zones and the wave velocities do not exceed 1 m/s in the shadow zones. Thus, the construction of the protective breakwater in Laspi Bay led to a decrease in wave velocities in the eastern part of its top. The breakwater leads to a decrease in wave velocities in the shadow zone by 4–6 times.



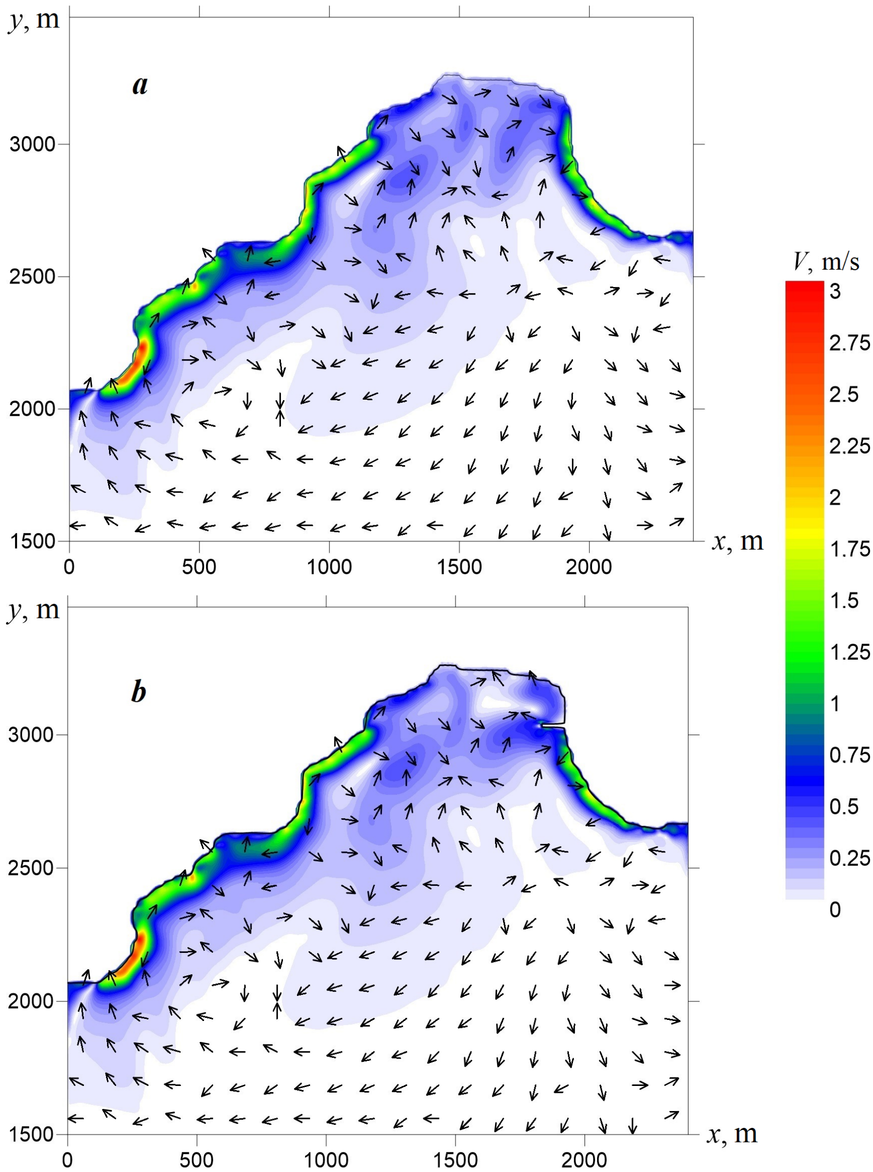
F i g . 2 . Significant wave heights in Laspi Bay for storms possible once a year: without taking into account the hydraulic structure (*a*); taking into account the hydraulic structure (*b*)



F i g . 3 . Significant wave heights in Laspi Bay for storms possible once every 25 years: without taking into account the hydraulic structure (*a*); taking into account the hydraulic structure (*b*)



F i g . 4 . Wave currents in Laspi Bay for storms possible once a year: without taking into account the hydraulic structures (*a*); taking into account the hydraulic structure (*b*)



F i g . 5 . Wave currents in Laspi Bay for storms possible once every 25 years: without taking into account the hydraulic structures (*a*); taking into account the hydraulic structure (*b*)

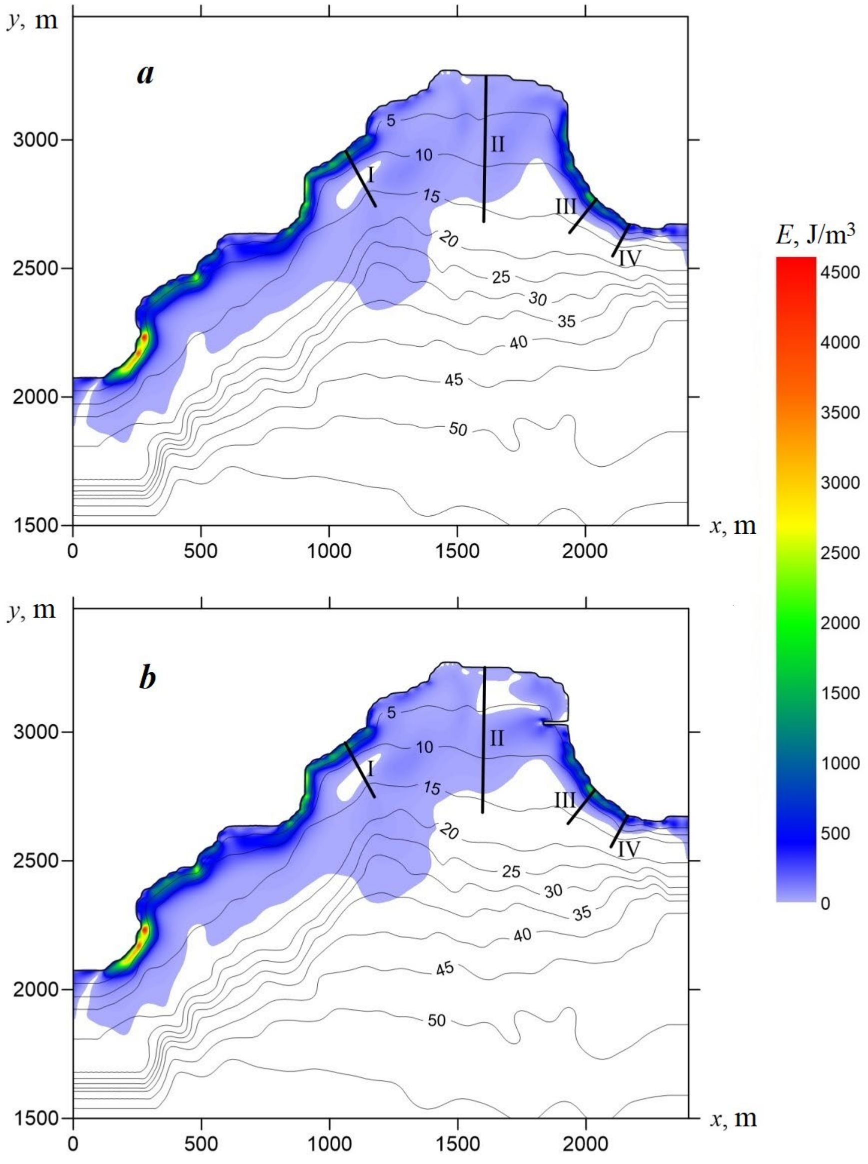
An assessment of the wave load on the bottom of Laspi Bay was carried out. For this purpose, the density fields of kinetic energy of the waves E were calculated. Fig. 6 shows the distribution of kinetic energy density in the bay during a storm possible once in 25 years. As can be seen, the intensity of the influence of wind waves increases as the depth decreases. In areas with depths of 10–20 m throughout the entire Laspi Bay water area and in shallower areas at its top, where the depth increases relatively smoothly, the kinetic energy density does not exceed 300 J/m^3. The same density values are typical for the central part of the bay down to depths of 35 m. Steep slopes are located almost along the entire perimeter of the bay at depths of 2–7 m. Here, the kinetic energy density increases to 500–2000 J/m^3 and it can reach 3000–4500 J/m^3 in the western end of the bay.

Fig. 6 highlights in bold the sections where the study of the bottom topography of Laspi Bay was carried out [2]. The sections are located perpendicular to the shore and cover all types of landscape identified in the bay. Section I is located in the western part of the bay, section II connects the top and the middle of the bay, sections III and IV are located in the eastern part of the bay. Concerning these sections, kinetic energy density profiles were obtained for a storm possible once a year, once every 5, 10 and 25 years (Figs. 7–9). These figures also show the bottom topography for each section, and the types of landscapes studied in [2] are indicated by numbers.

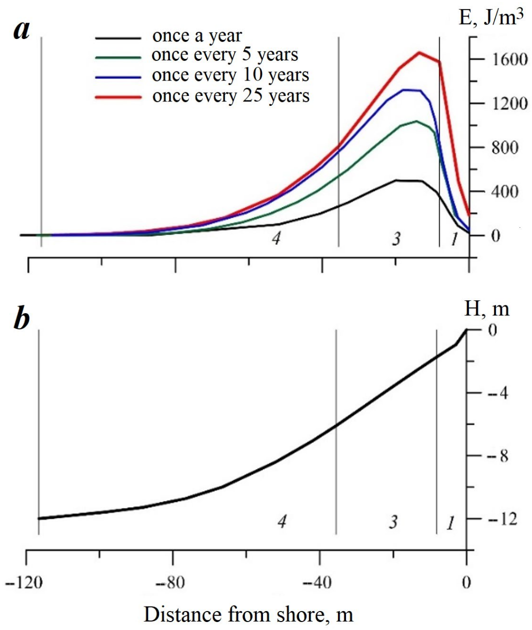
Fig. 7 shows kinetic energy density distribution and bottom topography for section I. It is evident that the energy loads for the storms under consideration are insignificant near the shore itself, where the block bench is located (number *1* in Fig. 7) [2]. With increasing depth, they increase sharply and reach a maximum value at a distance of about 15 m from the shore at depths of 2–7 m. In this area, a steep underwater abrasive coastal slope is located where Cystoseira dominates (number *3* in Fig. 7) [2]. During storms possible once a year, the maximum wave load is ~ 500 J/m^3; once every 5 years – ~ 1000 J/m^3; once every 10 years – ~ 1300 J/m^3; once every 25 years – about 1700 J/m^3. Then, at a distance of 30 m or more from the shore, at depths of 7–12 m, a gradual decrease in the energy load by 2–3 times occurs. Here, the underwater coastal abrasion slope with a predominance of Cystoseira and Zostera marina species extends (number *4* in Fig. 7) [2]. At depths greater than 12 m, the energy load effect is insignificant.

The energy load for section II, which is located at the Laspi Bay top, is minimal along the entire profile (Fig. 8). This is due to the small slopes of the bottom, as a result of which the dissipation of wave energy occurs at a fairly large distance from the shore.

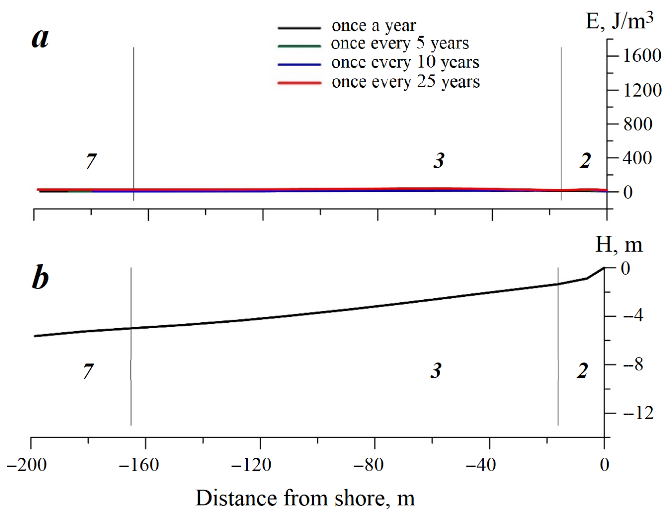
For sections III and IV (the eastern part of the bay) (Fig. 9), the energy load is insignificant near the shore, then it increases to its maximum at depths of 2–6 m, where also a fairly steep underwater slope with a predominance of Cystoseira is located (number *3* in Fig. 9). For section III, in case of storms possible once a year, the maximum energy load is about 500 J/m^3; during storms possible once every 5, 10, 25 years, it reaches 1100, 1300, 1600 J/m^3, respectively. For section IV,



F i g . 6 . Distribution of kinetic energy density in Laspi Bay for a storm possible once every 25 years: without taking into account the hydraulic structures (*a*); taking into account the hydraulic structure (*b*). Numbers I–IV indicate section numbers [2]



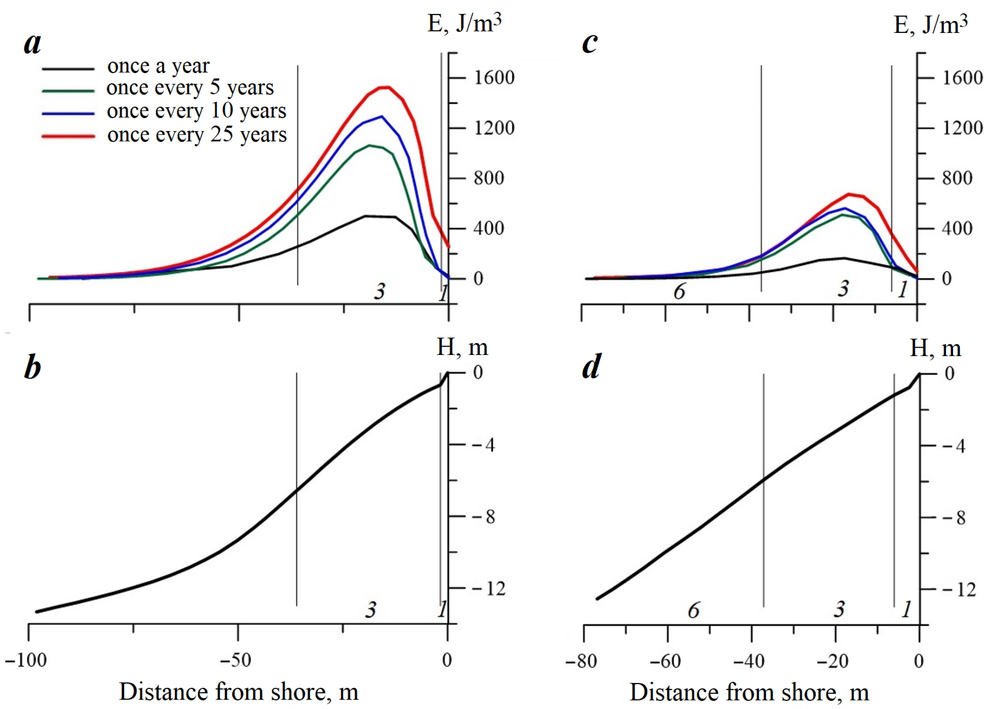
F i g . 7 . Profiles of kinetic energy density (*a*) and bottom topography (*b*) for section I. The numbers indicate bottom natural complexes from [2]



F i g . 8 . Profiles of kinetic energy density (*a*) and bottom topography (*b*) for section II. The numbers indicate bottom natural complexes from [2] the wave load decreases significantly, with 150 J/m^3 once a year and 500, 550, 700 J/m^3 once every 5, 10, 25 years, respectively.

Analysis of all obtained profiles of the kinetic energy density of waves (Figs. 7–9) shows that the wave load increases with distance from the shore reaching maximum values in the depth range of 2–7 m. Then, at depths of 7–12 m, a gradual decrease in wave load is observed. At depths greater than 10–12 m, wave load decreases sharply. The highest wave load values were obtained for sections I and III where they amounted to about 1600–1700 J/m^3, and slightly lower values were found in section IV (about 700 J/m^3). The minimum wave load values were obtained for section II where they did not exceed 50 J/m^3.

It can be concluded that during periods of extreme storms in the waters of Laspi Bay, the strongest wave effect occurs at depths of up to 10–12 m near coastal slopes with fairly steep bottom slopes. The middle part of the bay, devoid of bottom vegetation, is shallow, but is not subject to intense wave effect. It appears that the reason for the disappearance of bottom natural complexes in this area can be an increase in water turbidity caused by an increase in the influx of finely dispersed fractions due to anthropogenic impact on the shores of the bay.



F i g. 9. Profiles of kinetic energy density (*a*) and bottom topography (*b*) for section III; profiles of kinetic energy density (*c*) and bottom topography (*d*) for section IV. The numbers indicate bottom natural complexes from [2]

Conclusion

Calculations of wave fields for the Laspi Bay water area were performed with the numerical model SWASH. Data obtained from wave reanalysis were specified at the boundary of the computational domain. As a result of numerical experiments, significant wave heights and wave current velocities were obtained for storms that are possible once a year, once every 5, 10, 25 years in Laspi Bay. The calculations were carried out taking into account the protective breakwater built in the late 1980s and without regard to it.

During storms possible once a year, once every 5, 10 and 25 years, significant wave heights in the bay can reach 2.5–3.0, 4.0–4.5, 5.0–5.5 and 6.0–6.5 m, respectively. The zones of maximum wave velocities are located along the lateral boundaries of the bay. During storms possible once every 25 years, the increase in velocities to 1.5–3.0 m/s occurs along the coast at depths less than 10 m. Maximum wave loads on the bottom occur at depths of 2–7 m.

An assessment of the wave load on the Laspi Bay bottom showed that during storms of various regime conditions, the coastal slopes in the depth range from 2 to 12 m, where the kinetic energy density values increased to 500–2000 J/$м^3$, were most susceptible to wave effect. At this, the density can reach 3000–4500 J/m^3 in the western end of the bay. In the middle part of the bay, the energy load values are small. Therefore, the disappearance of bottom vegetation here could be not due to storm impact, but an increase in water turbidity caused by anthropogenic factors.

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Submitted 12.01.2024; accepted after review 30.01.2024;
revised 27.03.2024; published 25.06.2024

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All the authors have read and approved the final manuscript.