WINDY FLATS DEVELOPMENT ON THE UNTIDAL UKRAINEAN BLACK SEA

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Key words: Coastal zone, Windy flats, Set up, Beach, Sediment, Bench, Abrasion, Ukraine

Introduction

The Black Sea is untidal because the maximum value of tide near the Nothern shoreline is not greater than 0.08 m. That is why there are no typical tidal flats there. Nevertheless short-term changes of sea level take place. They are caused not by tides but by winds of gale force. If the wind is blowing landward, the water level near the shoreline is rising, if the wind is of the opposite direction, the level lowers relatively the average long-term value. The higher the wind velocity and the time of its action, the greater the amplitude of windy fluctuations of the level. It reaches the maximum in the tops of bays and harbours when windy vector acts along the normal to the shoreline, when land surfaces and nearshore sea bottom are the gentlest.

Such conditions are widely spread on the shores of untidal seas. They occur on considerably long sections on the shores of the Azov [8, 14], Baltic [7, 12] seas, along the shores of the Arctic Ocean [10, 14]. They are spread rather widely on the Black Sea shores as well.

The total length of the Black Sea shoreline is 4431 km. Conditions within the Ukraine, Romania, Bulgaria are the most favourable for the development of windy short-term changes of the level. These phenomena are observed along 902 km of shores, or 20.3% of the total length of the Black Sea shoreline. Within the Ukraine windy flats are spread along more 800 km of shares, mainly on the Northern part of the Sea, between Bakal Spit and Dnieprovskiy Liman (Fig.1), and many other limans. It was due to the noticeable differences from other regions that this part of the shore was singled out as a separate shore region by V.P. Zenkovich [13]. Considerable value of short-term windy fluctuations of sea level is one of such differences.

As one can see very shallow nearshore bottom of the Black Sea between Dnieprovskiy Liman and Bakal Spit within Ukraine attracted attention still 40 years ago. But since that time there have not been any considerable change in their study, due attention has not been paid to them. Investigations remained qualitative, which does not answer contemporary full, including quantitative, data on the coastal zone dynamics, and to deal with some scantily studied phenomena. Coastal Laboratory of State University of Odessa carried out long-term stationary research, which farmed the basis of the article results and conclusions.

Main differences and similarity between tidal and windy flats

In last time far the firstly windy underwater and upwater flats were studied on the North-Western and Northern shores of the Caspian Sea [5]. Areas of Nearcaspian Plain contiguous to the Sea are so gentle and smooth that during strong southern winds sea water moves several kilometers onto the land. When the wind is northern lowering of the water takes place, and the shoreline retreats several kilometers southward. These processes are accompanied by the development of currents with the speeds not quicker than 1-5 m/sec, but the average value is slower, of course. The surface of nearshore land and sea bottom exposed to erosion, the most typical forms of the relief being by wash channels and muddy flats, as on the shores of tidal seas. In the final sections of channels accumulative debris cones of sea water are formed (the erosive results sediment). These phenomena were analyzed by V.P.Zenkovich [14]. He was

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the first who made an attempt to determine basic characteristics of community and differ
between the influence of tides and windy changes of sea level within the coastal zone.

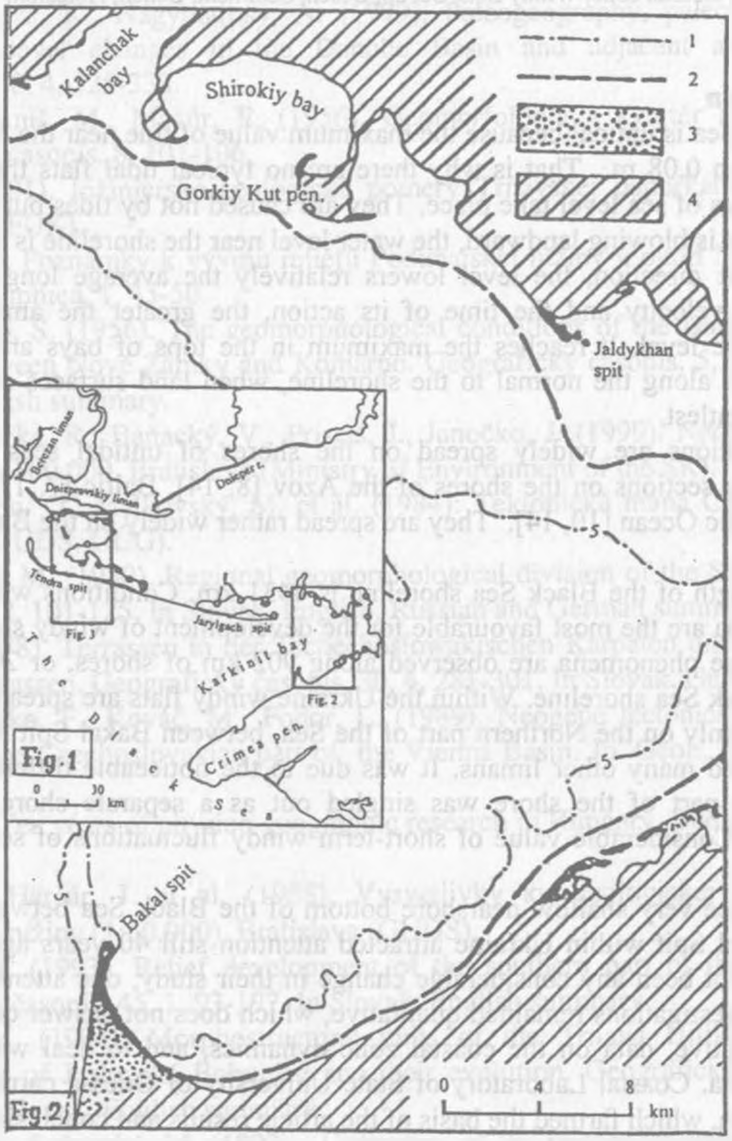

Fig. 1. Basic location of shares with windy flat on the Black Sea coast. Small circles are sites where instrumental long-term investigations are carried out.

Fig. 2. Detailed scheme of the location of windy flat on the near-shore bottom in the Eastern part of Karki Bay of the Black Sea: 1 - izobatic line, meters; 2 - outer boundary of windy flat; 3 - sandy and shell accumul forms of coastal relief; 4 - clayey deposit shores.

The greatest differences are in the origin and the regime of short-term sea le fluctuations. In general, tidal hydrodynamic processes are characterized by rhythm and t certain extent by constancy of difference between high tide and low tide on this or that sh sector. Windy sea level changing is, in general, of occasional character and has clea expressed unequal amplitude in one and the same place, but at different time. Along sh unequal amplitude is determined by the conditions that described above.

Other important difference is the value of the position between low level and high level within coastal zone. This difference can reach 10 m and more along tidal coasts. Windy sea level changes never reach such amplitude, they are always lesser, usual up to 2 or 4 m basically.

The third important difference is width of tidal flats. In general, on the shores of the World Oceans it exceeds width of windy flats considerably. This results in the fact that in most cases sea waves can exert influence on vaster area of coastal zone. At the same time windy set up exert influence along the whole shoreline of the World Ocean, while tidal waves act only along some part of the shoreline (in total, approximately till 30% of the Ocean shoreline long).

Fig. 3. Scheme of windy flat on the nearshore bottom in Egorlyck and Tendra bays of the Black Sea. For symbols see Fig. 2.

Fig. 9. Typical area of low shore land in the northern part of the Tendra Bay (location see at fig. 3).

Hydrodynamic conditions also create other differences - geomorphologic and lithologic. On the whole erosive and accumulative forms are expressed more vividly on tidal coasts than on the coasts influenced by windy fluctuations of sea level. For instance, erosive channels are wider, deeper, longer and bring mare sedimentary material, rates of drift accumulation are quicker. At the same time one finds a lot of common features between tidal and windy flats. Besides, the ones given above (similar velocities of currents, form of erosion and accumulation, submerged and drained areas of near-shore land, and other), we must mention the following ones.

Crossing profile of coastal zone becomes more complex in comparison with those sectors of untidal shores where there are almost no windy flats. When windy and tidal rising of level occurs, windy waves exert stronger influence on the shores and signs of this influence are more vividly expressed in the upper part of the profile. At the same time this process is accompanied by the formation of two, and not one, strips of the most intensive sorting of sediments by surf.

At windy and tidal sea level short-term change wetting and drying of deposits and rocks alternate correspondingly. Peculiar type of weathering is formed and wide and bottom flat benches (sometime with scarps) appear. On abrasive shores surfaces of benches are destroyed particularly actively when air temperature often changes from positive to negative and vice versa. Abrasion rates are higher and the dynamic is intensive [8, 11].

Under the influence of tidal and windy level changing zones and layers of muddy sediment accretion are formed. This phenomena is most vivid when shorelines are retreat and when mud supply to the coastal zone is abundant. When shorelines are evened usually mud is not accumulated especially under the conditions of set up changing of the sea level. Differences and common characteristics of coastal zone, which develops under the primary influence of tidal and storm-surge oscillations of sea level are taken into consideration when shore processes in the studied the Ukrainian region are analyzed.

Results of expeditional and analitic research

Main sites of natural observation are shown on Fig. 1. Doubled geodesic surveys of shores and nearshore bottom with the scale 1:500, sampling of sediments, measurement of currents velocities and wave dimensions during storms, concentration of suspended sediments, determining of the depth of drift layer on the beach and nearshore bottom have been carried out at these sites for past 30 years. All primary data of natural observations was processed in the Laboratory of National University of Odessa.

The shores which have been studied consist of clayey depositions of Neogene-Quaternary age. They contain on the average 5-7% of sand and coarser fractions from the whole quantity of depositions. Little strength of deposits means that shores can react essentially to the influence even of very small waves (during storm-surges) which are characteristic for wide shoals of the studied region between Bakal Spit and Dnieprovskiy Liman. High rates of cliffs reterat and nearshore bottom abrasion take place. On the sectors of active cliff locations the retreatings are up to 1.4-1.8 (average value is 0.4) m/year, and abrasive rates of nearshore bottom being 0.009-0.028 m/year within active benches locations. Such comparatively high rate was the main cause of beginning and development of abrasive forms. The total length of cliffs is 85.700 m, or 12.2% of the total length of the shoreline between Bakal Spit and Dnieprovskiy Liman.

Great length of shores and high rates of their abrasion, taking into account absence of rivers on the coast, can lead to the conclusion that abrasive source of sediments can be the most productive within noted coastal region. However, in reality it cannot ensure wide spreading of accumulative forms. The matter is that the great bulk (more than 90%) of sedimentary material is represented by the fractions finer than 0.1 mm, which compose not more than 1-3% in beaches. Usually they are carried out of the coastal zone. That is why accumulative forms have limited spreading, the length of each form being tens, sometimes hundreds of meters. Their width does not exceed 2-5 m. Often they are composed mainly of shells, supply of which to the shore is up to 0.3-0.4 kg/m^2 or up to 30-60 kg per 1 m of the shoreline length. In the composition of scanty beaches fraction 0.25-0.5 mm (51-55% of the total amount of sediment) prevails. Content of $CaC0_3$ equals 85-90%, which testifies to the prevailing of shelly detritus and little importance of terrigenious sedimentary material. Only large outer Tendra and Jarylgach spits were formed mainly due to the bottom alluvium sediment representing ancient Dnieper River terraces and occurring on the outer nearshore bottom.

The character of the shoreline which is subjected to the influence of short-term windy fluctuations of level is shown on Fig. 2 and 3. One can see that the depth of 5 m is far from the shoreline. Value of nearshore bottom gradients from 0.001 to 0.007 is usual. In this connection windy flat has considerable width and this width depends not only on the steepness of nearshore bottom, but also the values of windy lowering of the level during wind action from land-sector.

Recurrence of winds blowing from *NW*, *N* and *NE* is about 45% while from *SW*, *W* and *SE* only 33%. General geographic location of the studied shore shows that as to the recurrence windy lowering of level prevails over storm-surge rising of level. Northern winds are also stronger. For instance, northern winds having velocities greater than 15 m/s on the average during long-term period blow nearly 505 hours per a year, and southern winds having the same velocities blow only 190 hours per a year. Almost all winds with velocities greater than 20 m/sec blow from the North and the North-East (0.91%). Absolute maximum is 41 m/sec (*NE* direction).

Values of the hydrometeorological windy change of sea level are in connection with the regime of wind. V.P. Zenkovich [13, 14] observed storm-surges lowering of the sea level 1.5-2.0 m below zero water level. According to the observations on Ukrainian State hydrological stations minimum was equal –1.78 m, and maximum +1.01 m. But hydrological stations are located on the flat shore in local point. In the studied region the shore is enbayed with twisting shoreline. In bays and harbours (within Tendra, Karginskiy, Gorkiy, Shirokiy, Perekopskiy and other bays) values of windy decrease of level are lower (till –1.27 m during measurement) and of windy rising of level are higher (up to +2.83 during measurement).

Our observations showed that windy lowering of level equal to –1.0 m occurs once in 20 years, the one equal to –0.72 m occurs once in 6 years within opened and smoothed sectors of coast. Such values are observed when northern winds having velocity 20 m/sec blow. This means that width of windy flat is determined by the depth of 1 m, which is shown in fig. 2 and 3.

When southern winds blow, sea level rises develop by impact of set up. It can be equal +0.7 m once in 20 years and +0.5 m once in 6 years within sectors of opened and smoothed coast. Strong storms occurred, for instance, in October 1976, in February 1979, in March 1988, in November 1992, in January 2001. In November 1981 two gales from South occurred: November 2-3 (wind velocity was greater 15 m/sec with gusts up to 23 m/sec, lasted 20 hours) and November 9-11 (about 20 hours). During these gales low land about 500-900 m wide was flooded, especially on the shores of Tendra (Obloy shore site) and Egorlyck (Ochakovskoye shore site) bays (Fig. 4). There were instances when in Tendra bay sea-water invaded about 2000 in landward, in Perekop bay for about 600-700 m. The most noticeable processes of wave's dredging of shore forms with very shallow submarine slope occur at windy lowering of level with the value of –0,5 m and at set up rising –0.4 m. When the level decreases to –1.0 m and lower the greatest area of the bottom gets from sea water, that is why the line marking the depth of 1 m is taken as the outer boundary of windy flat (Fig. 2 and 3).

The area of all windy flats within the given limits of the region is rather big. In the boundaries of the Black Sea analyzed region (Fig. 1) equals: in total 920.4 km^2, including 1.48 km^2 in Egorlyck bay, 204.0 km^2 in Tendra bay, 164.4 km^2 in Jarylgach bay, and, 404.0

km^2 in the remaining part of Karkinit bay. However, these figures do not give objective idea about spreading of windy flats. That is why I suggest new unit of measurement which can serve to compare the degrees of spreading of windy flats along the Sea shores. It is the coefficient K_w which is found as the ratio of the area S km^2 to the length of the shoreline, L km:

$$K_w = S / L \qquad (1)$$

For the studied coastal region $K_w = 1.3$ km^2/km. This means that on each 1 km of the shoreline length windy flat occupies the area of 1.3 km^2. Correspondingly, the value of K_w can be found for each bay, harbour or other shores sector. For instance, for Egorlyck bay $K_w = 1.5$ km^2/km, which is greater than the average value in the whole coastal region. Calculating K_w we can also take into account overwater part of coastal zone, which is covered by sea water during storm-surges and set up action.

As it was stated above at windy rising of level cliffs are destroyed most actively. Fig. 4a gives the example on "Dangeltip" stationary site. During 1964-1993 average rate of abrasion was equal 0.8 m/year. On other sites the upper part of abrasive terraces is higher than sea level, for instance, on "Karga" site (Pig. 4b). In this case at set up rising of level wave's sandy ridge is formed on the sea margin of the terrace.

During several years distances at which the upper part of the low cliff retreats during the storms of different force have been measured. Correspondingly, the level rises to various heights. On the whole influence of 21 storms with 0.5-1.0 m height waves were measured. It turned out that the greater the wind velocity and the higher rising of level, the quicker cliff retreats (Fig. 5). This allowed establishing the dependence of the values of cliff retreat W_a on the values of set up ΔH. The coefficient of correlation turned out to the equal $r = 0.87 \pm 0.04$. The diagram of the function $H_a = f(\Delta H)$ has the following version:

$$W_a = 0.62\,\Delta H \qquad (2)$$

The received equation of regression is representative under the conditions of sediment deficit, absence of beach at cliff base, occurrence of loamy and loess depositions within the coast.

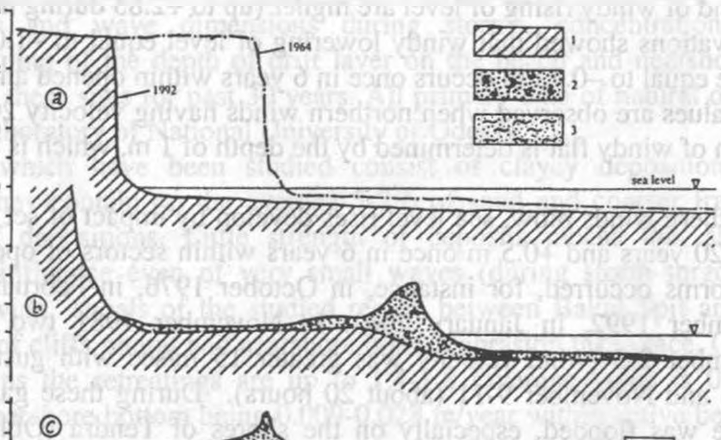

Fig. 4. Typical windy flat crossing profiles of the Black Sea which develop under the impact of storm surges and set up changes of the level: 1 - clayey deposits; 2 - sand with admixture of shells; 3 - mud with admixture of sand and shell debris; a - shore with active cliffs, 1964 and 1993 - years of instrumental surveys; b - shallow shore with abrasive terrace, inner old non-active cliff and modern beach small ridge; c - very shallow bottom and low nearshore land, with small primary beach ridge.

If in front of the coastal cliff there is rather wide abrasive near shore bottom terrace, how it is shown on Fig. 4b, such cliff is stable and is not eroded by waves even during the highest set up. But during particularly strong storms when windy level rise exceeds 0.5 m, sediments are supplied onto the surface of the terrace. They are accumulated here. The terrace is sealed with the layer of sediments. If the development of this process is progressive the abrasive terrace can become accumulative. It is one more way of the development of shores under the conditions of short-term windy (hydrometeorologic) rising of sea level.

Considerable part of shores of the studied region is very gentle, smooth, and surface marks of nearshore low land are not greater than 1 m (Fig. 4 and 9). If there are enough sediments, as for instance to the north-east of Bakal Spit, a small beach is formed as shown on Fig. 4, or accumulative terrace is formed. If there is no beach during storms, nearshore low land is freely flooded by sea water, and on the shores scours, furrows, alluvials, salted areas are most vividly expressed. The given examples show the main ways by which windy (storm-surge) rising of level influences sea shores of the region during storms.

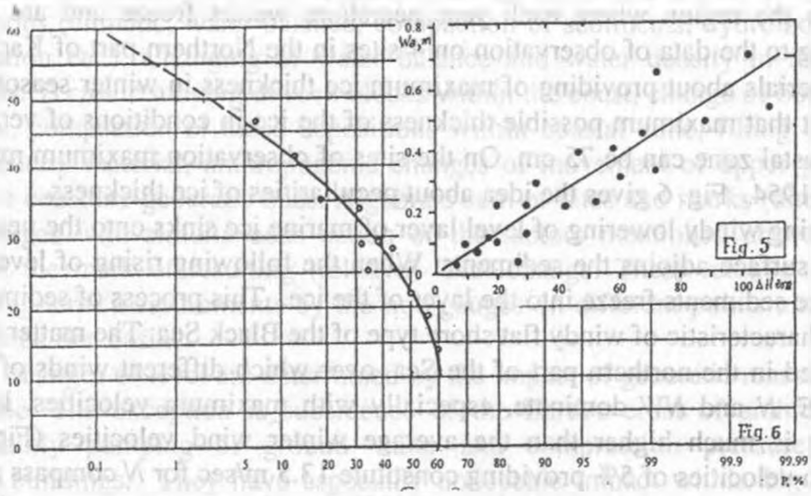

Fig. 5. Diagram of dependence of clayey cliff retreat W_a (m/year) on the values of windy rising of the level ΔH (cm) in Jarylgach Bay abrasive shores of the Black Sea by results of natural long-term experiments.
Fig. 6. Prosperity curve of maximum thickness of marine ice for average winter season 1945-1992 near the northern Karkinit Bay shore, the Black Sea.

Influence of currents and marine ice

Windy fluctuations of sea level conducive to important lythodynamic peculiarities of coastal zone. In particular, during storms when sea level rises under the influence of storm-surge, larger waves approach the shoreline. Clay cliff and nearshore bottom deposits are intensively eroded and concentration of suspended sediments in water increases. Natural field measurements showed that when waves are 0.5 m high (medium storm degree for the shallow aquathory) silt charge in the shallow water reaches 500-600 mg/l and even 1700-1900 mg/l. This means that in the interval of 0-1 depth simultaneously there can be from 2 to 8-6 kg of sediments per 1 m of the shore length. If we take into consideration that this process acts along almost 800 km of the shore it turns out that during each the storm thousands of tones of sediments are in suspended position.

However, during calm, when the wheather is quiet and sea water have minimum mobile, concentration of suspended sediment are usually 10-15 mg/l basically is silt. This means that the remaining part of suspension must to dump onto the bottom after every storm. Sources of sediments (inclutiding abrasive) have supplied drifts during hundreds of years and a thick layer of mud must have been farmed an the bottom. In reality during the calm muddy layer constitutes 0.01-0.25 m. Hence it follows that the great bulk of suspended drifts move off into the opened sea. During storms short-term sea level increases for tens of centimeters. Hydrostatic gradient is formed, its vector being directed into the open sea. After stows currents with considerable (before 1.0-1.2 m/sec) velocities directed mainly into the open sea are to be observed. These compensate currents testify to the measurement of levels on the shallow water region near the shore and in the open sea. Duration of this process usually does not exceed 2-3 hours. It turns out that clear water containing up to 10-15 mg/l of sediments displaces to the shoreline direction from the open sea, and suspended water with concentrations up to 2000 mg/l is taken off. This original pump is typical for the shores with windy flats. It occurs as well on the shores of tidal seas [5, 8, 14], and is the most vivid when storms coincide with the level of high tide, and following calm coincides with the end of the storm at low tide level. It is the mechanism that represents the main factor of evacuation of suspended sediments out of the coastal zone.

Important role of marine ice in morphodynamic and lithodynamic processes is another important peculiarity of the studied shores of the Black Sea. These shallow and law shores belong to the region where each year nearshore waters freeze and are covered with ice. According to the data of observation on 4 sites in the Northern part of Karkinit Bay in 1945-1992 materials about providing of maximum ice thickness in winter season were received. It turned out that maximum possible thickness of the ice in conditions of very shallow sections of the coastal zone can be 75 cm. On the sites of observation maximum registered value was 46 cm in 1954. Fig. 6 gives the idea about peculiarities of ice thickness.

During windy lowering of level layer of marine ice sinks onto the nearshore bottom and its lower surface adjoins the sediments. When the following rising of level the ice comes to the surface sediments freeze into the layer of the ice. This process of sediment saturation is in general characteristic of windy flat shore type of the Black Sea. The matter is that these shores are situated in the northern part of the Sea, over which different winds of northern compass points *NE*, *N* and *NW* dominate, especially with maximum velocities. In icy season their providing is much higher than the average winter wind velocities (Fig.7). For instance, maximum velocities of 5% providing constitute 13.5 m/sec for *N* compass point, 19 m/sec for *NE* and 13 m/sec for *NW*. Velocities of 10% providing equal correspondingly 11, 16.4 and 12.2 m/sec, and for 25% - 10, 16 and 9 m/sec in average of long-term period.

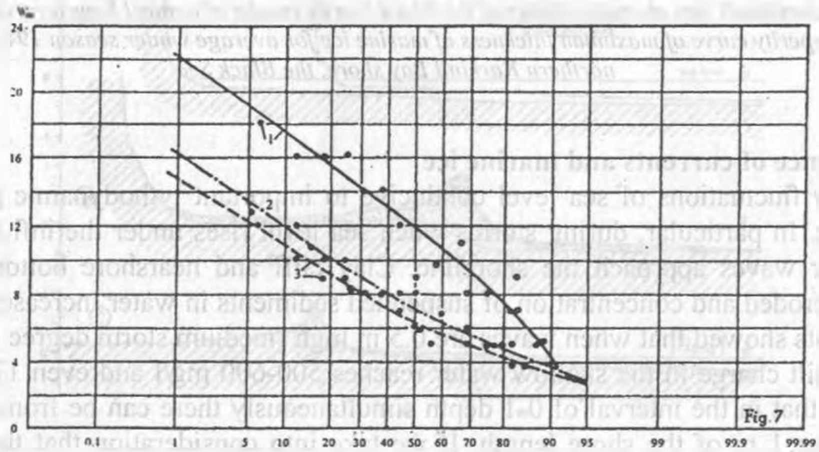

Fig. 7. Prosperity curve of maximal wind velocity during icy period by data of observation in Khorly Station, 1945-1992. Wind directions: 1 - NE; 2 - NW; 3 - N.

Concentration of drifts of marine ice layer inside reaches 0.5-0.8 kg/m^2. The most often ice adjoins the bottom near the shore at the distance up to 250-300 m from the shoreline. It can be calculated that on the average there can be from 123 to 240 kg of sediments per long 1 m of the shore length. In spring when ice is destroyed, under the influence of northern winds it is carried into the open sea and carry sediments along. Of course, some part of ice remains near the shoreline; some part melts on the spot, and that is why quantity of ice sediments carried away into the sea is much less than calculated 125-240 kg/m. Nevertheless, ice is an important factor of evacuating sediments into the sea under the conditions of very shallow nearshore bottom and location of specific shore type with windy flats.

It should be noted that in winter in fact there is no influence of sea waves on the shores of the studied region. Such influence is prevented by ice layer [14]. Influence of storm-serge fluctuation of sea level is also hampered. That is why during the period of sea water freezing, the water evacuation with suspended sediments into the open sea by the nearshore currents is negligible. As it was shown above, this mechanism acts during warm season of the year. During frosty season of the year drifts are evacuated into the open sea mainly with ice layer. At the same time within the shores of tidal seas, currents also act when nearshore water area is covered with ice. That is why drifts are carried off into the open sea under the influence of various genesis currents as well.

Possible impact of relative sea level rise

Relative rise of the Black Sea level is determined by combined impact of hydrocratic and geocratic reasons (climatic, water balance, compaction of sediments, hydroizostasis, sea bottom sedimentation etc.). Changing of water balance and water density in the Sea are hydrocratic reasons. Tectonic moving of rock blocks within the coast, change of bottom basin volume of the sea, compaction of loose depositions within coastal zone, filling of the Sea basin with sedimentary material, anthropogenic changes of movement of upper part of the Earth's crust on the coast are geocratic ones. Algebraic sum of rates and marks (directions) of the Sea level changes with simultaneous action of the factors mentioned above give the summary rate and the mark of resulting (relative) level change. These relative values are received during long-term measurements by the tide-gauges on different points and complex approach of the Black Sea basin.

The slowest changes of level are determined by the impact of geocratic reasons. Trends are the most stable. The exception is subsidence of the Earth's crust of anthropogenetic genesis: it is mainly pumping of ground water and compression pressure of large constructions and buildings. They have especially noticeable impact within big cities and urban aglomerations. Since they are absent in the investigated region (Fig.1) and the coast is characterized by the low intensity of developing, the impact of such subsidence of the Earth's crust is not essential.

As for the compaction of coastal sediments, to the greatest extent they affect Kinburn Peninsula, Tendra and Jarylgach spits. Because of this factor rates of relative rise of the sea level can be 25-30% higher than in the regions of spreading of metamorphic and crystalline rocks of high strength. Filling of the Black Sea basin with sedimentary material carried off the land increases the rate of relative rise of the level at 10-15%.

The most essential variations of rates and long-term trends of sea level change are connected with the peculiarities of water balance. At present the disastrous increase of water mass in the World Ocean and corresponding unusually intensive rise of sea level during the closest 100 years are predicted [2, 4] in connection with the influence of «greenhouse effect» and corresponding changes of the Planet's climate. According to different calculation methods, that used by various scientists, the value of sea level rise can constitute from 0.3 to 6.0 m in 2100 in different regions.

According to the observation carried out in the watershed of the Black Sea [3, 9] during the last 3-4 decades noticeable changes of such climatic characteristics as temperature and humidity of overland atmospheric layer, including the areas where coasts with windy flats are spread, took place. For instance, in the period 1923-1964 the average long-term December temperature in Ochakov equaled –0.4°C, in. Khorly –0.2°C. In 1955-1999 it increased essentially and constituted +0.3°C and +0.7°C accordingly. At the same time, the average temperature of summer season decreased, but the change was below by comparison to winter.

In particular the average long-term July temperature was 22.3°C in Odessa and 23.4°C in Khorly during 1923-1964. But in 1955-1999 it turned out to be correspondingly 21.9°C and 23.1°C. Therefore the general increase of the average temperature in the XX-th century is rather clearly pronounced.

The amount of atmospheric precipitation also changed in region of shares with windy flats location within Ukraine. In 50-60's sharp jump in the precipitation quantity took place, since the middle 70's comparatively low rising has been observed. In the period from 1970 to 1999 the average long-term amount of precipitation constitutes on stations of Vilkovo 528 mm/year, on Odessa 501 mm/year, on Ochakov 464 mm/year, on Khorly 452 mm/year, etc. It is 73-81% higher than in the first half of last century, the average being 76.4%. Similar phenomena take place within the Black Sea watershed in total.

The increase of atmospheric precipitation amount caused the increase of alluvial water run-off. The longest river of Europe Danube characterized by the increase of liquid run-off, the annual growth being 0.91 km^3/year or +0.27% a year of total discharge to the Sea (+0.5% of the Danube run-off) in the average during the last 35 years. In 1965-1990 the Dnieper river ran-off increased at 6.0 km^3 or in the average +0.24 km^3/year. This equals 0.57% a year of the liquid run-off. Corresponding increase took place with all great rivers of the Black Sea drainage basin. At the same time the decrease of annual values of water evaporation from the surface of the sea aquatory from 470-485 km^3/year in the 50's to 320-340 km^3/year in the end of the 80's of XX century occurred. The main reason lies in the pollution and reorganization of the structure of surface microlayer water on the whole area of the Sea aquatory [3, 6]. As a result, the rise of the Sea level became more active, which was accompanied by the increase of the amount of atmospheric precipitation (at 25%) falling on the whole area of the Sea aquatory.

Of course, water exchanging of the Black Sea with the Mediterranean Sea through Bosphorus Strait and with the Sea of Azov through the Kerch Strait also livened up. However, these straits are so narrow and shallow that they cannot ensure in the moment the full discharge of additional quantity of water at once. Algebraic sum of all elements of the water balance determined the resultant member of the balance, which is equal +1.6 km^3/year during the last 50 years.

Combined influence of the elements of reorganizing water balance is reflected in the curves of the level change received by the observation in different points of the investigated shore. For instance, on the base (strong) Odessa station in 1921-1949 the average rate of relative rise of the level equaled 0.9 mm/year, but already in 1950–1973, when the incoming elements of the balance became more active, it reached 4.5 mm/year and in 1974-1999 already 8.3 mm/year. Similar tendency was observed for Khorly station (Fig. 8) situated on Gorkiy Kut Peninsula (Fig. 2). Noted curve is typical for Eastern part of the studied region (Fig. 1).

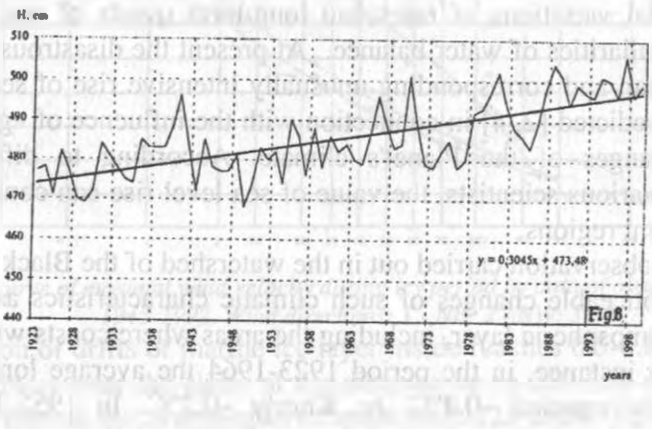

Fig. 8. Change in the yearly values for the Sea level (H, cm) according to the observation data from the Khorly Station for 1923-1999.

The tendencies shown above give the right to assert that in future long-term rising of the level can create real danger of passive submergence of windy flat shore type, taking into consideration very low surface of nearshore land (Fig. 9), little changeability of shore relief and low wave energy. The maximal length (209.5 km) of the shore sector with very low marks (less than 2 m over the zero sea level of 1990) of nearshore land is spread in Karkinit Bay between Crimea Peninsula and Dnieprovskiy Liman (Fig. 1).

Assuming that the tendency discovered in the second half of the XXth century will continue in the XXIth. century as well in Karkinit Bay the rate of the sea level rise will become 36 times greater, i.e. by the end of the following century it will constitute 133 mm/year. This means that the final value of the level rise will be 2 m over the modern zero sea level. However, in connection with the rhythmical nature of changes of basic climatic characteristics and elements of water balance within the Black Sea this value will be much lesser. Taking into consideration very low nearshore land in the area (Fig. 4, 9); where shores with windy flats are spread, all this creates real danger of passive flooding. That is why it is reasonable to consider 3 main scenarios for end of XXI century: final sea level rise on 0.5 m, 1 m, and on 2 m in 2100.

On condition that the sea level rises on 0.5 m, flooding in the average of 1.33 km^2 on 1 km of the shape length (km^2/km) is possible. One meter rise will lead to the flooding in the average on the region already of 2.12 km^2/km, 2 m rise – of 3.90 km^2/km. Therefore, it is 7.3, 11.6 and 21.4 times more than along the shores of the limans, located between Danube Delta and Dniestrovskiy Liman (Chapter 2). Taking into consideration the length of low shoreland with windy flat and the character of their relief (calculations of areas were carried out on the map of 1:10.000 scale), the area of possible submergence will constitute accordingly 125.7 km^2, 232.5 km^2, and 356.5 km^2 with various noted scenarios. In the natural conditions livening of set up and increase of the area of windy flat should be expected, and as a result negative impact of the Sea will spread on the greater area.

Thus, in comparison with the other types of shores within Ukraine the windy flat shore type can be subjected to much stronger impact of the Black Sea level rise in connection with the change of climate by the end of XXI century. Such prediction must attract attention of nature users and experts working out the problem management of economy of Ukraine.

Conclusions

During several dozens of year's instrumental observation and investigation along the Black Sea coast, between Dnieprovskiy Liman and Bakal Spit region especially, has been carried out. This regional shore is one of the most significant where windy flats are spread under the conditions of untidal sea. Wave's influence on the shores is weakened, which is promoted by wide shallow waters of nearshore bottom. That is why short-term storm-surge and set up fluctuations of sea level under the influence of strong winds and waves are of basic importance. The influence of windy fluctuations of sea level is very similar to the influence of tidal phenomena. As the result similar morphodynamic and lithodynamic processes develop. However, there are differences as well. On the surface of nearshore bottom forms of relief created by erosive and accumulative processes develop. Quantitative and numerical characteristics of windy flats spreading expressed as area per a unit of shore length is suggested. At rising of sea level during storms short-term flood of nearshore low land with windy flats takes place on the investigated areas. During the flood within studied coast areas three main processes are vividly expressed:

(*a*) usual flood, during which scours, furrows, debris cones and salted areas are formed, but in fact, shoreline itself does not change during after-storm period;

(*b*) processing of small beaches at weak roughness and break of beaches at strong roughness with the following flood of near-shore land;

(*c*) abrasion of cliffs with the shoreline retreat without flood of nearshore land.

This article gives information about scantily investigated problem of the development of one tidal shores analogue on untidal seas under the influence of windy changes of level on the example of the Black Sea shores between Bakal Spit and Dnieprovskiy Liman.

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