Role of river transport and coastal abrasion in forming modern coastal and marine sediments in the Northwestern Black Sea

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Abstract. The Danube, the Dniester, the Southern Buh and the Dnipro rivers discharge into the north-western part of the Black Sea. Their total catchment area is 1,458 million km². The length of the coastline with active abrasion processes in this segment is about 60 km. This is 26% of the total length of the coastline (from the estuary of the Danube, Odesa Oblast, to the city of Ochakiv, Mykolaiv Oblast). The article analyses the methodological basis for the calculation of solid river runoff and material entering the sea as a result of coastal destruction, summarizes their main characteristics and proposes an algorithm for quantitative calculations. For river runoff, it is based on the dependence of the amount suspended matter on the volume of water discharged per unit time. For quantitative calculations of coastal abrasion, data on the dynamics of changes in the configuration of the coast have been used with the help of GIS systems. It has been shown that one of the main factors influencing the removal of solid material from the land is the flow velocity, which also influences the volume of water per unit time. This leads to an increase in the mobility of terrigenous components. An important factor is the mineral and physical condition of the rocks eroded along the river’s path. Man-made structures (hydroelectric plants, dams) significantly reduce the mobility of water and consequently the amount of material transported. They have the greatest effect on the transport of bottom constituents. One of the main factors influencing the intensity of abrasion is wave activity with wave heights exceeding 0.5 m. The average annual number of such waves is 165 days. The current total annual mass of sediment discharge from the Dniester (to the Dniester estuary) is 2,280 thousand tons, from the Southern Buh – 192 thousand tons (to the Dniester-Buh estuary) and from the Dnipro – 800 thousand tons (to the Dniester-Buh estuary). Most of this material is deposited in the estuaries and about 10% is discharged directly to the sea, which is (in thousand tons): suspended – 11,981, bottom – 488. The Danube sediment discharge to the Black Sea is estimated at 12,143 thousand tons. The calculated total annual mass of material entering the sea through coastal abrasion in various parts of the coast is (in thousand tons): Lebedivka-Kurortne – 501.8; Karolino-Buhaz-Chornomorsk – 184.5; Kryzhanivka-Rybakivka – 201.6; Rybakivka-Ochakiv – 7.2, making a total of 895.1. About 158.8 thousand tons are involved in the formation of the particle size distribution of beach sediments.

Key words: coastal abrasion, river sediment, suspended and bottom components, beach sediments.

Роль річкового виносу та берегової абразії в формуванні сучасних прибережно-морських відкладів північно-західної акваторії Чорного моря

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Анотація. До північно-західної частини Чорного моря розвантажуються – Дунай, Дністер, Південний Буг, Дніпро. Загальна площа їх водозбору становить 1,458 млн км². Протяжність берега з активними абразивними процесами на цьому сегменті складає близько 60 км, що дозволяє 26% від загальної довжини берегової лінії (гирла Дунаю, Одеська обл. до м. Очаків, Ми-
Introduction

The supply of solid material from the land, via river runoff and coastal erosion, is of paramount importance for the accumulation of sediments on the northwestern Black Sea shelf. This material is particularly important for forming sediments along the coastline (beaches, headlands, spits, bars, submarine ridges), which, combined with factors of marine hydrodynamics, determine their final morphology and composition. Solid material from the land is transported by rivers in suspended and bottom sediments, the quantitative ratio of which is variable.

The main waterways of the northwestern Black Sea region are the Danube, Dniester, Southern Buh, and Dnipro. Several important factors affect the overall rates (quantitative and qualitative) of suspended sediment and bottom material removal from the land: the catchment area, the slope and speed of the river, the volume of water removed, the composition of the rocks drained by the river water, and the degree of regulation. The influence of each of these factors and their combined effect is unique to each catchment.

The hydrodynamics and calculation of river discharge into the northwestern part of the Black Sea are studied in Gâştescu, 1998; Bondar, 2000; Panin and Jipa, 2002; Jaoshvili, 2003; Shuisky and Stoian, 2011; Panin, 2016; BME, 2018; Organ, 2020; Jeleapov, 2022. Most of them concern the calculation of the suspended fraction and are based on monitoring observations. The best study in this respect is the Danube River.

In 2000, C. Bondar and V. Blendea, as part of the Black Sea Fluxes project (UNESCO), made the first significant synthesis of the different approaches to the methodology for calculating the solid fluxes of the Danube and provided quantitative indicators based on monitoring data from Romanian researchers over the last 150 years (Bondar and Blendea, 2000).

In 2003, S. Jaoshvili, within the framework of the project “Pilot project 2 – Black Sea sediment fluxes” under the auspices of UNESCO, presented the results of the processing of long-term studies of quantitative indicators of suspended sediment flow to the Black Sea by all river systems before and after regulation. The calculations were based on hydrometric observations and reinterpretation of previous monitoring station readings.

In the 2017-2019 period, the “Interreg Program of the Danube Oblast” updated the data of the Danube monitoring stations and created an interactive map of suspended sediment along the entire riverbed (BME, 2018). It shows a significant dependence of the quantitative and qualitative composition of suspended sediment on the degree of regulation and flow velocity.

Scientists from I.I. Mechnikov Odesa National University have made a significant contribution to the study of sedimentation in the Danube and Dniester rivers (Vykhovanetz et al., 2005; Shuisky and Stoian, 2011; Orhan, 2020). These studies emphasize the significant impact of the degree of river regulation on the quantitative indicators and distribution of sediments in the mouth and estuary parts.

Scientists from the University of Chisinau have also studied the problem of calculating the terrigenous component of the Dniester. The paper by A. Jeleapov presents the results of the correlation of solid discharge and water volume per unit time based on measurements from monitoring stations located near hydropower plants. It is also shown that the regulation of the river system leads to a decrease in the amount of transported material (Jeleapov, 2022).
The study of the coastal zone and coastal abrasion of the northwestern part of the Black Sea is covered by I.P. Zelinsky, V.P. Zenkovich, G.M. Aksentiev, Y.D. Shuisky, E.A. Cherkez, et al.

In (Aksentiev, 1959) the author proves that soil erosion and coastal slope erosion are almost the same, which leads to the accumulation of material on the coast.

Zenkovich (1965) presented data on sediment transport and heavy mineral concentrations along the coastal zone. He also attempted to calculate the abrasion rate for different parts of the Black Sea coast.

Shuisky and Vykhovanetz (1989) considered the influence of exogenous processes on the state of shoreline formation and specified the geological structure of abrasive shores from Cape Veliky Fontan to Zhebriyanska Bay.

The paper (Zelinskii et al., 1993) focuses on landslides processes in the northwestern part of the Black Sea, in which the authors reveal their nature and impact on the geological environment.

Among the most recent works, the publication (Medinets and Cherkez, 2022) within the framework of the EU-funded CBC BSB 889 PONTOS project is worth mentioning, which shows changes in the coastline of the northwestern Black Sea from 1980 to 2020. The study was based on satellite imagery data and their comparison using a GIS system.

However, most of the previous studies did not focus on a comprehensive approach, considering the importance of each of the factors affecting the total terrigenous removal from the land, and they did not consider the data on material supply due to coastal abrasion, taking into account the geological structure, lithological composition of the coastal rocks and sea hydrodynamics.

This study aims at summarizing the previous research and based on the authors’ observations and calculations, to identify the main factors and quantitative indicators of modern terrigenous transport from the rivers of the north-western Black Sea coast to the Black Sea, considering the contribution of each river system and calculating quantitative indicators of marine abrasion in different parts of the coast.

Materials and methods

The authors collected the actual material during the study of rock complexes drained by the main waterways of the northwestern Black Sea region, the study of rocks in the coastal zone, and the study of particle size distribution and mineral composition of beach sediments along the coast. The materials of publications and open sources of domestic and foreign researchers were also studied, in particular (Zelinskii et al., 1993; Jaošvili, 2003; Lehner et. al., 2011; Shuisky and Stoian, 2011; BME, 2018; Jeleapov, 2022).

Graphical, cartographic methods and GIS technologies were used for calculations and interpretation.

Research results and analysis

1. Main factors influencing river sediment transport and their ranking

The quantification of sediment transport by rivers is itself multifactorial. Each catchment has different characteristics and influencing factors, but in general, they can be ranked in order of importance.

*The first* most important factor influencing the quantitative indicators of terrigenous runoff is the slope of the rivers. It is directly related to the flow velocity, which in turn is related to the mobility and size of the particles. The greater the flow velocity is, the larger the mobility and size of the debris components. This relationship has been confirmed by numerous observations and calculations for river systems in the region (Earle, 2015).

*The second* most important factor is the degree of regulation of the river system – artificial engineering structures in the flow path (dams, reservoirs, hydropower plants, bridges, etc.). They significantly reduce the flow velocity, resulting in the deposition of most of the bottom sediment and a significant amount of suspended sediment in front of the structures. This pattern is confirmed by empirical calculations for rivers in different regions (Walling, 2006; Milliman and Syvitski, 2013).

*The third* most important factor is the physical and mechanical properties of the rocks being eroded by the river and the conditions under which they occur. Numerous observations have shown that at the same flow velocity, sedimentary rocks of weakly cemented polymineral and multigrained composition, as well as rocks cut by the river in a non-laminar direction, are more susceptible to river abrasion. Magmatic and metamorphic rocks are more resistant to river abrasion. The degree of compaction, secondary transformation and fracturing of these rocks is also important. River abrasion is greatly enhanced by an increase in flow velocity and a change in the direction of water movement (Panin and Jipa, 2002; Chakrapani, 2005).

*The fourth* most important factor is the volume of water passing through a given point per unit of time. It is directly related to flow velocity and channel width. The volume of water discharged correlates well with quantitative indicators of suspended sediment trans-
port between points. An example of this correlation for the Danube is shown in Figure 1 (Vykhovanetz et al., 2005; Shapiro, 2009; BME, 2018).

The fifth most important factor is the size of the river basin. It has the least influence on the quantitative indicators of sediment transport to the water surface. If a river is flat and has a larger catchment area than a mountainous river, the amount of material it carries will still be less due to its slower flow (Chakravorty, 2005).

2. Quantitative calculations of sediment transport by the rivers of the northwestern Black Sea region

The work on the calculation of the sediment yield of the rivers of the northern and northwestern Black Sea region is not systematic and is based mainly on the data on the suspended sediment component. However, different researchers give different proportions of suspended and bottom components. For example, for shallow rivers, according to (Mykhailov, 1986; Alexeevskyi, 1990), the proportion of sediment transported to the sea is on average 10% of the suspended sediment. For the Danube, according to the estimation of (Orhan, 2020) 3-4% of the suspended sediment is transported to the bottom. The report (BME, 2018) for the Danube allocates 0.1% of the suspended sediment to the bottom.

The Danube – is the largest river in Western and Central Europe. It rises in the Black Forest in Germany (678 m above sea level) and flows through 10 countries: Germany, Austria, Slovakia, Hungary, Serbia, Croatia, Romania, Bulgaria, Moldova, and Ukraine. It flows into the Black Sea through the delta and the territories of Romania and the Odesa Oblast of Ukraine. The river is 2,857 km long and covers an area of 817,000 km². In the upper part it has the characteristics of a mountain river with a flow rate of up to 2.8 m/s, in the middle and lower parts it has the characteristics of a plain river with a flow rate of up to 1 m/s. The average gradient is 0.27 m/km. In the lower part, the Danube is divided into three branches: Kilia, Sulina, and Georgieva, which form the delta (Khilchevskii, 1990; Gâştescu, 1998; Orhan, 2020).

In its upper reaches, the Danube drains crystalline rocks of the Proterozoic (gneisses, migmatisites, amphibolites) and sedimentary rocks of the Triassic, Jurassic, Cretaceous, and Neogene (sandstones, siltstones, mudstones, marls, limestones, dolomites), which differ in mineral composition and thickness. In the middle and lower reaches, the river cuts through sedimentary and volcanoclastic sedimentary rocks of the Triassic, Jurassic, Cretaceous, Neogene, and Anthropocene (limestone, marl, siltstone, sandstone, dolomite, tuff, dacite, sand, clay, and loam).

The modern Danube is largely regulated, with numerous hydropower power stations, dams, and weirs built on its course and its tributaries. The construction of hydropower plants began in the early 20th century. The Iron Gate HPP (commissioned in 1972) and Iron Gate 2 HPP (commissioned in 1984) have had the greatest impact on reducing the amount of sediment transported downstream (Meybeck et al., 2003; Walling, 2006; Panin et al., 2016). The locations of artificial structures on the Danube and its tributaries are shown in Figure 2. As can be seen from the figure, only the lower part of the Danube, which is not regulated, can be considered an active area for the collec-

Fig. 1. Correlation between water discharge (X-axis in m³/s) and suspended sediment discharge (Y-axis in kg/s) at the Zimmicea (Romania) and Svishtov (Bulgaria) gauging stations. The scales are logarithmic (BME, 2018).
tion of terrigenous material (Fig. 2). Its area is about 104.5 thousand km² (12.8% of the total area).

To determine the quantitative indicators of terrigenous transport, we partially used the material from the Danube Transnational Program project (BME, 2018), which summarizes the observations of suspended sediment components over the last 30 years and data from monitoring stations downstream of the Iron Gate 2 HPP (Table 1).

The table shows that as the Danube approaches the sea, the amount of suspended sediment is reduced by splitting the continuous river flow into 3 delta branches, increasing the width of the total flow and consequently reducing the flow velocity. This pattern is well illustrated in the chart (Fig. 3).

Using this chart and the extrapolation method, it is possible to calculate the amount of suspended sediment transported through the Kiliya estuary to the Black Sea, which is about 6,270 thousand tons per year. Similarly, the export of suspended matter, taking into account the extrapolation, was obtained for the Georgievsky (3,117 thousand tons per year) and Sulinsky (2,345 thousand tons per year) branches. The total removal will be 11,732 thousand tonnes per year.

This correlation was used to obtain numerical values of the material transported to the sea. Thus, the total amount of suspended sediment transported is 11,732 thousand tons per year, which is lower than the data reported in (Jaošvili, 2003).

Let’s compare the early data reported in (Mykhailov et al., 1988). We see a significant decrease in the material from 87,800 thousand tons per year to 11,732 thousand tons per year, which is 13.36% of the original value.

Taking into account the ratio of suspended and bottom components of 3-4% (Orhan, 2020), after the regulation of the Danube, the amount of bottom components of terrigenous runoff transported to the Black Sea by all arms will be about 410 thousand tons per year.

The fractional composition of the suspended and bottom components was determined at a monitoring station in the lower Danube (on Romanian territory) (BME, 2018). The suspended sediment included the fractions of coarse-grained siltstone (10%), fine-grained siltstone (75%), and pelitic siltstone (15%) (determined by the turbidity method).

In the bottom part, the following fractional composition was determined using the sampler method with an exposure time of 10 minutes: pelitic – 5%, siltstone – 51%, psamite – 44%.

**The Dniester** – rises in the Ukrainian Carpathians at an altitude of 818 m above sea level, flows through

<table>
<thead>
<tr>
<th>Monitoring station name</th>
<th>The river kilometer</th>
<th>Weight of material in suspension (thousands of tons per year)</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isaccea</td>
<td>100.20</td>
<td>21,458</td>
<td>1986-2014</td>
</tr>
<tr>
<td>Ceatal Izmail</td>
<td>80.50</td>
<td>19,664</td>
<td>1986-2014</td>
</tr>
<tr>
<td>Periprava (Kiliya branch)</td>
<td>20</td>
<td>8,997</td>
<td>1986-2015</td>
</tr>
<tr>
<td>Sfântul Gheorghe Harbour (Georgievsky branch)</td>
<td>8</td>
<td>3,517</td>
<td>1986-2015</td>
</tr>
<tr>
<td>Sulina (Sulinsky branch)</td>
<td>2.5</td>
<td>2,514</td>
<td>1986-2014</td>
</tr>
</tbody>
</table>
Ukraine and Moldova, and empties into the Dniester estuary near the town of Bilhorod-Dnistrovskyi. The total length of the Dniester is 1,362 km, and its catchment area is about 72,000 km² (Khilchevskii, 2008). In the upper reaches (the Carpathian Dniester) it has a mountainous character, while in the middle and lower reaches it is flat. The flow velocity in the upper (mountainous) part is 0.3-2 m/s. In the middle reaches, within the Dniester Canyon, it is 0.5-1 m/s. In the lower reaches it is up to 0.7 m/s. The average slope of the riverbed is about 0.56 m/km (Gilka et al., 2005).

In the upper reaches, the Dniester flows through Meso-Cenozoic sedimentary rocks of the Carpathian Mountains (limestone, marl, sandstone, clay, sand). In the middle reaches, the river drains sedimentary rocks of the Proterozoic (sandstones, shales), Paleozoic (sandstones, marls, limestones, mudstones, dolomites), Mesozoic (sandstones, marls, limestones, clays) and Precambrian crystalline rocks (granites, migmatites), forming the so-called Dniester Valley. In its lower course (below the Dubasari hydroelectric power station), the Dniester cuts through weakly consolidated Neogene (clays, sands, sandstones, limestones) and anthropogenic (clays, sands, sandstones) rocks.

The main differences between the Dniester and the Danube are the absence of a braided delta, the flow velocity, the slope and width of the riverbed, and the seasonality. The Dniester flows directly into the estuary through two small tributaries and its waters join the sea through a narrow strait at the village of Zatoka.

Like the Danube, the Dniester is heavily regulated, so its sediment flow is much reduced. The first hydroelectric power station, Dubasari, was built in 1954. In 1983 the Dniester Hydro Power Plant (HPP) was commissioned and in 2002 the Novodnistrovska HPP was built (Fig. 4). The part of the river system downstream from the Dubasari HPP to the Dniester estuary is of great importance for the transport of solid matter (Fig. 4), with an area of 11.75 thousand km² (16.3% of the total basin area).

Fig. 3. Correlation graph between distance to the sea and suspended sediment mass for the Danube using the example of the Kiliya branch. Distance to the sea (km). Mass of suspended sediment (million tons per year). $y$ – linear equation of the trend line. $R$ – coefficient of determination.

Fig. 4. The Dniester basin (marked in blue) and the area of active accumulation of terrigenous material transported to the sea (marked in red). Green color – Dniester River and its main tributaries. Blue – rivers with active sediment accumulation. Yellow stars – artificial structures (Lehner et al., 2011).
The amount of solid material transported by the Dniester River into the Dniester estuary was calculated based on long-term observations and generalizations (Jaošvili, 2003; Kovalyshyna et al., 2021), as well as measurements in 2022 at the Bender monitoring station before and after the construction of the HPP (Fig. 5). After the construction of the Dubossary HPP (313 km upstream), a significant decrease (by a factor of 3) in the amount of suspended matter was recorded at the Bender plant, located ~100 km downstream of the above HPP.

At the Bender gauge, the average annual discharge of suspended sediment in the Dniester River is 1,463 thousand tons (Jeleapov, 2022). Considering the ratio of suspended sediment to bottom sediment for the Dniester (Shuisky and Stoian, 2011), the weight of the bottom component is about 438.9 thousand tons. In total, the annual Dniester transport to the monitoring site (Bendery village) will be 1,901.9 thousand tons. According to the calculations (Shuisky and Stoian, 2011) carried out at the monitoring station near the mouth of the Dniester River, the total annual sediment discharge to the Dniester estuary is 2280 thousand tons, i.e. 379 thousand tons more. This means that there are no significant obstacles to the replenishment of terrigenous material between Bendery and the estuary of the Dniester.

It has been estimated (Milliman and Syvitski, 1992) that about 10% of the terrigenous material enters the sea through the Dniester Strait, and most of it is deposited in the estuary. On this basis, about 228,000 tons of terrigenous material is discharged to the sea annually, of which 159,600 tons are suspended and about 68,400 tons are sediment.

The Southern Bug is a flat river that rises in Podillia, Khmelnytskyi Oblast, at an altitude of 320 m above sea level. It flows through the regions of Khmelnytsky, Vinnytsia, Kirovohrad, Mykolaiv, and Odesa and empties into the Buh estuary of the Black Sea (Fig. 6). It is 806 km long and covers an area of 63.7 thousand km². The flow velocity in the upper part is 0.5 m/s. In the middle part, the width of the riverbed decreases significantly, it cuts through crystalline rocks and as a result the flow velocity increases to 1.5 m/s. In the lower reaches, the channel widens again and the flow velocity decreases to 0.2-0.5 m/s. The average gradient of the river is up to 0.4 m/km. In the suburbs of Mykolaiiv, the river valley gradually widens from 1.5-2 to 5 km and forms an estuary. It flows into the estuary of the Buh River.

In the upper and middle reaches, the Southern Bug cuts through resistant Precambrian crystalline rocks of the Ukrainian Shield (granites, migmatites) and Neogene sedimentary rocks (clays, sands, sandstones, limestones). In the lower reaches, it erodes sedimentary rocks of Paleogene (clays, sandstones, marls), Neogene (clays, sandstones, limestones), and anthropogenic (sands, clays, sandstones) age before entering the estuary.

The Southern Bug is regulated in the middle and lower reaches. The first small hydroelectric power station was commissioned in 1929 near the town of Pervomaisk. Since then, 38 small hydropower plants have been built. The latest one, the Novooleksandrivska HPP, was built in 1999 and is located 179 km from the estuary. The current area of active terrigenous collection after the construction of the last HPP is 6.54 thousand km² (about 10% of the total area).

According to estimates (Jaošvili, 2003) made before the construction of the Novooleksandrivska HPP, the total amount of terrigenous material transported from the Southern Buh to the Dnipro-Buh estuary was 320 thousand tons per year. According to our calculations, the commissioning of the latter HPP resulted in a 35-40% reduction in the mass of solid material transported to the estuary, which will amount to 128 thousand tons per year in absolute terms. Thus, the current total annual discharge through the Southern Buh will not exceed 192 thousand tons. The suspended fraction is about 172.8 thousand tons, and the bottom fraction...
is about 19.2 thousand tons. The Dnipro-Buh estuary discharges an order of magnitude less directly into the Black Sea, estimated at no more than 17.2 thousand tons per year for the suspended component and 1.9 thousand tons per year for the bottom component.

The Dnipro is a shallow river that rises on the southern slopes of the Valdai Upland (Russia) at an absolute altitude of 252 meters above sea level. It flows through Russia, Belarus, and Ukraine. The river is 2,285 km long and covers an area of 504 thousand km². Most of the flow (about 80%) is generated in the upper reaches (Yatsik et al., 2002). The flow velocity at the confluence of the Desna River is variable and ranges from 0.3-1.2 m/s, while in the middle and lower parts the flow velocity stabilizes and averages 0.6-0.7 m/s (Dehodiuk and Dehodiuk, 2006). The average gradient is 0.11 m/km. After the Kakhovka HPP, the Dnipro forms an extensive delta, about 60% of which is covered by plains, and flows into the Dnipro estuary at Hola Prystan in Kherson Oblast.

In the upper reaches, the Dnipro erodes sedimentary rocks of the Devonian (clays, sandstones, marls, limestones, dolomites), Carboniferous (clays, coal, marls, limestones), Jurassic (siltstones, sandstones, marls, limestones), Cretaceous (marls, sands, sandstones, limestones), Paleogene (sands, sandstones, marls) and Neogene (sands, clays). In the middle and lower parts it cuts through crystalline rocks of the Ukrainian shield (granites, migmatites), Cretaceous sedimentary rocks (limestones, sandstones, marls), Jurassic (sandstones, clays, limestones), Paleogene (sandstones, clays, marls, sands, mudstones) and Neogene (sandstones, clays, sands, limestones).

Many engineering structures have been built on the Dnipro, such as hydroelectric power stations, dams, dikes, and reservoirs, which have significantly altered the flow rate and affected the overall removal of terrigenous material. The Dnipro HPP was the first to be built (1927-1932). The Kakhovka HPP was commissioned in 1956, the Kremenchuk HPP in 1960, the Sredniodniprovska HPP in 1964, the Kyiv HPP in 1966, and the Kaniv HPP in 1975 (Fig. 7). The closest to the delta is the Kakhovka HPP, located 90 km from the estuary. Due to the proximity of the Kakhovka HPP to the estuary, the river flow does not have time to restore the flow capacity, which slows down the quantitative indicators of terrigenous material removal (Malakhov et al., 2010; Obodovskyi et al., 2020). According to (Romanenko, 2004), the total reduction in the removal of solid material by all technical structures on the Dnipro is 40 million tons per year, which is more than 90% of the total. At present, the part of the river system downstream from the Kakhovka HPP to the Dnipro-Buh estuary is of great importance for the transport of solids (Fig. 7). Its area is 13.35 thousand km² (2.6% of the total basin area).

While the total weight of material transported before the regulation was 2,100 thousand tons per year (Jaošvili, 2003), the current solid discharge can be estimated at 800 thousand tons per year. About 720,000 tons of them are suspended solids and about 80,000 tons are bottom sediments. It is estimated that an order of magnitude less is discharged directly into the Black Sea from the Dnipro-Buh estuary – 72,000 tons per year for the suspended component and 8,000 tons per year for the bottom component.

Thus, the four main river systems – the Danube, the Dniester, the Southern Buh, and the Dnipro – currently discharge about 15,414 thousand tons per year, of which about 12,469.1 thousand tons of terrigenous material is transported directly into the Black Sea.
material reach the water body directly, while the rest – about 2,800 thousand tons – is deposited in the estuaries. Before the river systems were regulated (about 100 years ago), the total sediment discharge into the north-western Black Sea was much higher and, according to our calculations, amounted to more than 92,000 thousand tons per year.

After the destruction of the Kakhovka dam on 6 June 2023, the amount of terrigenous material carried by the Dnipro increased. At present, it is difficult to quantify this increase, but taking into account the general methodological approach used in our work, this increase can be up to 10-12%.

The solid material transported by the rivers is redistributed by hydrodynamic processes when it enters the active zone. Wave action removes the pelitic and siltstone fractions and carries them out to sea, while the psamite fraction is distributed along the coast by currents, forming accumulation bodies.

Considering the grain size distribution of the already formed beach sediments (Nesterovskyi et al., 2022; Nesterovskyi et al., 2023), it can be argued that no more than 10% of the total amount of material transported by the rivers is used for their formation. In absolute terms, this amounts to about 488 thousand tons per year.

3. Coastal abrasion material supply

Shoreline rocks have a direct influence on the supply of source material for the formation of accumulating sediments along the shoreline. The rate of shoreline abrasion is influenced by geological (petrographic composition of the shoreline rocks, neotectonic movements, landslides, water content), geomorphological (height and slope of the shore, configuration of the shoreline, distance from the water’s edge), hydrological (wave action) and anthropogenic factors.

Hydrodynamic conditions, i.e. waves, are the main factor in the destruction and transport of sediments. Waves with high energy potential, especially storm waves, greatly accelerate the abrasion and redistribution of solid sediments along the shore and coastal waters.

The steepness of the shore and the depth of the adjacent sea affect the dissipation of wave energy. The distance from the shore to the cliff is also important; the closer the cliff is, the more effective the destruction (Davies, 1973).

Given the same values for wave action and bank steepness, areas of stable rock – well-cemented sedimentary, metamorphic, and igneous rocks – will be less affected by erosion. Poorly consolidated sedimentary rocks and rocks with active fracturing are more likely to be subject to erosion (Scott and Moe, 2017). An important factor in the increase in fracture activity is the development of landslide processes, which in turn are associated with neotectonic movements and the nature of rock alternation in the coastal zone (Zelinskii et al., 1993).

In modern conditions, anthropogenic activity is a significant factor influencing coastal degradation. The uncontrolled construction of numerous holiday homes and tourist resorts directly in the coastal zone creates additional conditions for the intensification of landslide processes and coastal abrasion. In addition, coastal protection structures installed in areas of active urbanization of the coastal zone interfere with the natural hydrodynamics and stimulate coastal erosion in other places. This, in turn, leads to changes in the

Fig. 7. The Dnipro basin (marked in blue) and the area of active terrigenous material accumulation transported to the Dnipro-Buh estuary (marked with red color). The Dnipro River and its main tributaries are shown in green. Blue – rivers with active sediment accumulation. Yellow stars – artificial structures (Lehner et. al., 2011).
coastal morphology and redistribution of solid material inputs into the sea from different abrasion areas (Stanica, 2000; Shuisky et al., 2017).

The total length of the coastline in the studied area (Danube-Ochakiv) is about 230 km. The coastal zone that is actively subject to erosion is about 60 km, which is 26% of the total length. The eroded shores are in 4 coastal sections, which differ in height, slope steepness and rock composition: Lebedivka-Kurortne (18.5 km long), Karolino-Buhaz-Chornomorsk (8 km long), Kryzhanivka-Rybakiwka (31.5 km long), and Rybakivka-Ochakiv (2 km long) (Nesterovskyi et al., 2022).

The geological structure of the coast is formed by sedimentary rocks of the Neogene and Quaternary systems (Fig. 8).

The Neogene sediments are represented by rocks of the Sarmatian, Meotian, Pontic and Kuyalnikian stages.

The rocks of the Sarmatian stage are submarine and are exposed only at the bottom of estuaries, their erosion is minimal. The rocks of the Meotian stage are involved in the structure of the lower part of the coastal zone above the water’s edge. They are not widespread and some fragments are eroded or submerged. The sediments are represented by «mute» clays, in some places with sandy, calcareous interlayers of sands of polymineral composition.

The Pontic deposits directly overlie the Meotian. They are intermittent. Above sea level, they are found only in the Kryzhanivka-Rybakiwka section. They are represented by limestones, clays, siltstones and sandstones.

Deposits of the Kuyalnitska Suite are developed on the coastal slopes of the localities: Kryzhanivka – Rybakivka, Rybakivka – Ochakiv. In most outcrops, they are represented by interbedded sands and clays. The sandy facies are predominantly of fine and medium grain, feldspar-quartz composition.

Quaternary sediments are widespread in the coastal sediments and their outcrops. They are mostly represented by clays, loess, and loess-like loams, with fossil soils in the upper part.

Landslides occur along the entire route as the abrasive banks develop. They develop at contact of rocks of different compositions and ages. Landslides are most common at the contact of Pontic limestone and Meotian clay, Pontic limestone and Kuyalnik sand clay deposits, Quaternary loams, and Neogene deposits. The landslide activity increases with the irrigation of the contacting rocks. The landslide processes are intensified by neotectonic movements, which are widespread along the coast and have different amplitudes. This contributes to abrasion and an increase in the mass of material entering the surf zone.

The following formula has been used to calculate the annual mass of coastal abrasion:

$$m = \rho \times l \times w \times h,$$

where \(m\) is the mass of eroded rock (kg), \(\rho\) is the density of the rock (g/cm³), \(l\) is the length of the elementary segment of the coastline (m), \(w\) is the width of the elementary segment of destruction (m/year), and \(h\) is the height of the coastline segment (m).

Coastal elevation data are derived from open-source SRTM (Shuttle Radar Topography Mission) data, which are derived from satellite-based radar topographic surveys of the Earth’s surface. The images are in raster format with a resolution of 90 m and a height accuracy of 1 m. Areas where coastal defences have been built on the coastline to prevent coastal erosion have been excluded.

![Fig. 8. Schematic geological section of the coastal area of the north-western Black Sea coast. Symbols: 1 – loess clay; 2 – silt; 3, 4 – coarse- and fine-grained sands; 5 – limestone; 6 – clay; 7 – sand with shell debris; 8 – sandy silts; 9 – sea level (Zelinskii et al., 1993).](image-url)
The length of the elementary segment was calculated using a GIS system and measurements between the elevation points were obtained and averaged between 60 and 120 meters.

To determine the width of the elementary segment in abrasive areas, we used data from the PONTOS project (Medinets et al., 2022), which used Landsat and Sentinel satellite images from 1980 to 2020. For our sites, the width of the elementary segment will be Lebedivka-Kurortne – 1.7 m/year, Karolino-Buhas-Chornomorsk – 1 m/year, Kryzhanivka-Rybakivka – 0.5 m/year, Rybakivka-Ochakov – 0.1 m/year. The visualization of the areas of abrasive banks with different widths of elementary segments is shown in Fig. 9.

The average density for different rocks for abrasive banks is (g/cm³): Quaternary loess loams and clays – 1.95; Meotitic clays – 1.9; Pontic limestones – 1.6; Sands and sandstones – 2.04.

The annual mass of abrasion for each site was calculated taking into account the specific lithological composition of the rocks and the degree of their interaction with the waves. On this basis, it was distributed as follows (in thousands of tons) Lebedivka-Kurortne – 501.8 tons; Karolino-Buhas-Chornomorsk – 184.5 tons; Kryzhanivka-Rybakivka – 201.6 tons; Rybakivka-Ochakov – 7.2 tons. The total annual weight of material from all abrasive banks is about 895.1 thousand tons.

The waves erode areas of the coast with different grain size distributions of rocks such as pelite, siltstone, and psamite. All of this mass is subjected to the action of the waves and currents, which together sort the material. Pelitic and siltstone particles are removed from the total mass and transported beyond the active hydrodynamics, while larger fractions participate in the formation of coastal beach sediments. We have demonstrated this pattern by studying particle size distributions along the entire northwestern Black Sea coast. The dominant fraction in all areas from the Danube to the Dnipro is psamite with a size of 0.25-0.5 mm (Nesterovskyi et al., 2022).

Based on this, only psamite components are involved in the actual formation of accumulating beach sediments from coastal abrasion material, the amount of which, according to our calculations, is no more than 158.8 thousand tons per year.

Conclusions

1. The main factors influencing the quantitative indicators of solid material removal from the land by the waterways of the north-western Black Sea coast are flow rate; water volume per unit time; degree of river regulation; and physical and mechanical condition of the drained rocks. The influence of each of these factors is individual for each river system.

2. The main factor in reducing the amount of solid material transported by river runoff over the last 50-100 years has been its significant regulation. After regulation, terrigenous runoff decreased by Danube ~86, Dniester ~9, Southern Buh ~40, and Dnipro ~62.

3. The current annual supply of the north-western part of the Black Sea with solid matter by river discharge is (thousand tons/year, suspended/sedimentary components): Danube – 11,732/410; Dniester – 159.6/68.4; Southern Buh – 17.2/1.9; Dnipro – 72/8. The total amount is 12469.1 thousand tons per year. After the regulation, the total flow of solid material decreased by ~80,000 thousand tons per year. After the destruction of the Kakhovka dam in 2023, it is
expected that the discharge of the Dnipro into the estuary will increase by 10-12%.

4. The main factors of coastal erosion in the north-western part of the Black Sea are active wave activity, lithological composition of rocks, coastal configuration, and anthropogenic activities.

5. The natural destruction of coastal rocks in recent years has shown a decreasing trend due to artificial shoreline reinforcement, which reduces the supply of material by abrasion.

6. The mass of terrigenous material discharged into the water from the areas of abrasive shoreline development is (thousand tons per year): Lebedivka-Kurortne – 501.8; Karolino-Buhas-Chornomorsk – 184.5; Kryzhanivka-Rybakivka – 201.6; Rybakivka-Ochakov – 7.2. The total amount of terrigenous material due to coastal abrasion is currently estimated at about 895.1 thousand tons per year.

7. River runoff is of great importance for the formation of the mineral composition of the accumulating beach sediments of the northwestern part of the Black Sea. However, due to its significant decrease in the last 50-100 years, the difference between its contribution and that of coastal abrasion has significantly decreased. Thus, in the northern segment, near the estuary of the Dnipro-Buh with the sea, the mass of material due to coastal abrasion exceeds the mass of river runoff.

8. The total amount of terrigenous material entering the sea and participating in the formation of accumulating beach sediments has significantly decreased in recent years and tends to decrease further. This leads to a lack of detrital material to maintain the material balance in coastal areas and to an increase in the dynamics of redistribution of mobile material along the coastline and possible destruction of already formed accumulations.

References


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