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Longshore Sediment Transport Pattern Along the Romanian Danube Delta Coast

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ABSTRACT

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Measurements of shoreline change between 1962 and 1987 were used to construct a sediment budget and to derive net longshore sediment transport rates for the Romanian Danube delta coast. The resulting pattern was in good agreement with the potential longshore transport pattern predicted by the wave energy flux based on wave measurements between 1972 and 1981. Due to the general coast orientation, the longshore sand transport is almost unidirectional southwardly all year long. Hence estimates for the net longshore transport were as high as high 2,350,000 m^3/year. Because of this high intensity longshore transport and also due to a reduction of Danube sediment and the interruption of longshore transport by shore-perpendicular structures, much of the coast is undergoing erosion. Near the Sfantu Gheorghe mouth, a rapidly migrating barrier island acts as a substantial sink for littoral sand producing a downdrift deficit in the sand budget.

ADDITIONAL INDEX WORDS: *Black Sea, sediment budget, wave climate, potential longshore sediment transport, coastal engineering structures.*

INTRODUCTION

Many deltas around the world have been receding due to anthropogenic alteration of both water and sediment discharge, coupled with vigorous longshore sediment transport. In the case of the Danube delta, erosion is threatening the ecosystem of wetlands and coastal lakes. Furthermore a chronic sand deficit extends downdrift of the delta coast, and the loss of bathing beaches threatens an important tourist economy at the seaside resorts of the southern sector of the Romanian Black Sea shore. Four factors have been identified to explain the recessional behavior of the Danube delta (ROMANIAN CENTER FOR MARINE GEOLOGY AND GEOECOLOGY—RCMGG, 1994): (1) delta evolution by alternate channel extension, which naturally diverts most of the river sediment discharge to a single distributary, starving the earlier built lobes; (2) a general decrease in the river sediment discharge due to damming, dredging, and agricultural practices in the Danube drainage basin; (3) river mouth jetties and harbor jetties which disrupt the longshore sediment transport pattern, and deficient harbor and channel dredging practice; and (4) relative sea level rise. Tidal processes are not important because the mouth of the Danube is a microtidal environment.

This situation is also found in other microtidal deltaic coasts such as the Nile (SESTINI, 1992; STANLEY, 1996), the Po (CAPOBIANCO *et al.,* 1995), and the Ebro (JIMENEZ and SANCHEZ-ARCILLA, 1993; PALANQUES and GUILLEN, 1995). The construction of dams, dredging, the entrapment of water and sediments, the decrease in the rainfall, have been cited as important factors in decreasing fluvial sediment discharge. Such a reduction amounts to 95% of the total load in the Ebro (PALANQUES and GUILLEN, 1995) and 98% in the Nile (SESTINI, 1992). At the same time the acute orientation of particular deltaic coastal segments to the principal wave direction tends to produce high rates of longshore sediment transport. This is the case on the Nile delta coast, where net longshore sediment transport rates as great as 1,200,000 m^3/year estimated (QUELENNEC and MANOHAR, 1977), or the Volturno delta, a small cuspate delta on the western coast of Italy, where the maximum net rate was estimated to be 1,760,000 m^3/year (BENASSAI *et al.,* 1995).

The objective of this study was to analyze the present behavior of the Romanian Danube delta coast. Waves with a high angle of attack drive an intense longshore transport of sand. The construction of harbor jetties, river jetties, and poor dredging and disposal practices have altered substantially the shoreline dynamics.

STUDY AREA

Geological Setting

The Romanian Black Sea coast (Figure 1) stretches over 245 km from the northernmost distributary of the Danube (Chilia) at the Romania-Ukraine border to the Bulgarian border to the south. The Romanian coast can be divided into a

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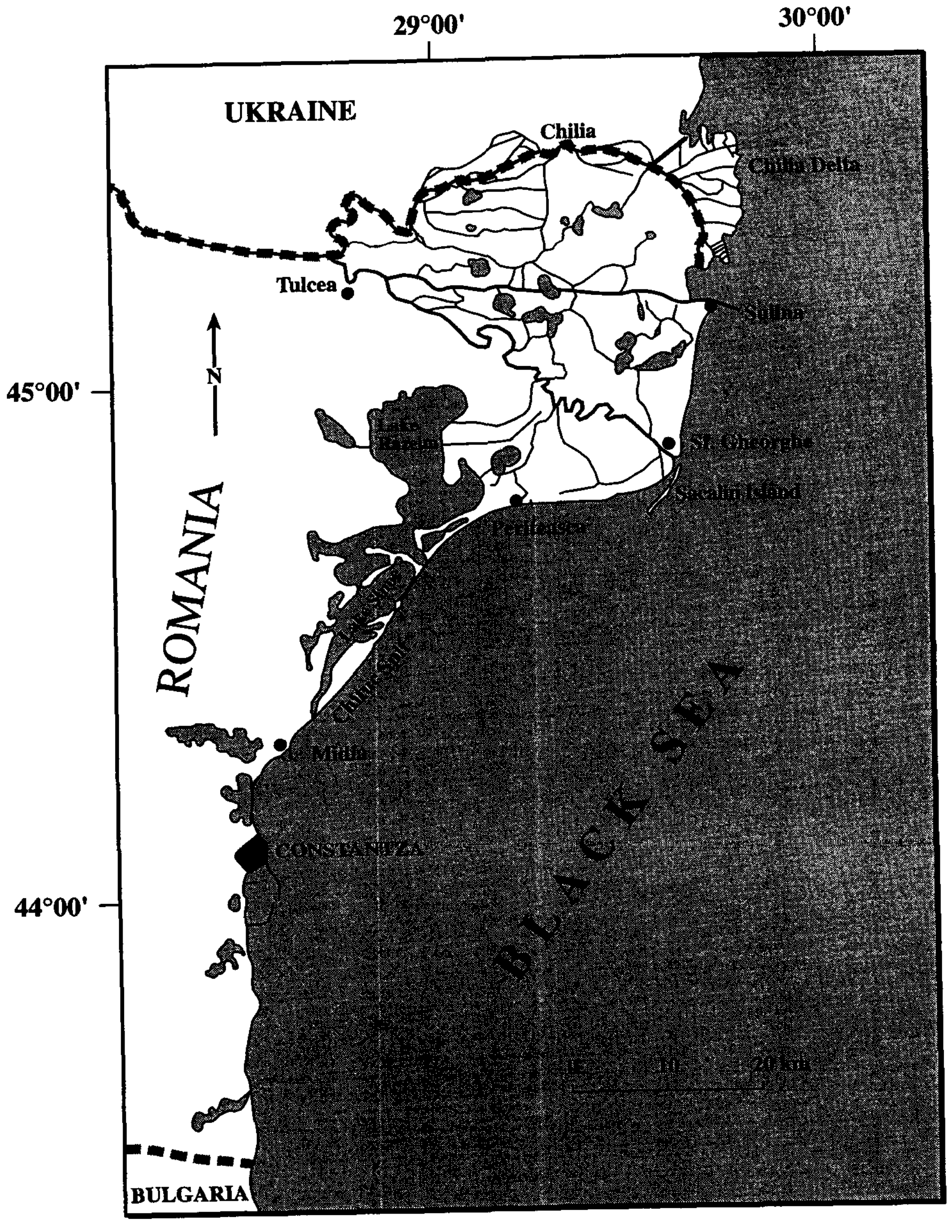

Figure 1. Romanian Black Sea coast. Danube delta coast (including the adjacent, genetically related, baymouth barrier in front of Razelm-Sinoe lagoons) extends from Chilia to Midia.

northern unit and a southern unit using geographic and geomorphic criteria (RCMGG, 1994). The northern unit is the low-relief Danube delta coastal zone, and the southern unit is characterized by eroding cliffs of loess and limestone, protected in places by narrow beaches (CHARLIER and DE JULIO, 1985; RCMGG, 1994).

The Romanian deltaic coast consists of the lobes of three major distributaries. From north to south these are the Chilia, the Sulina, and the Sfantu Gheorghe (Figure 1). The coast south of the Sfantu Gheorghe distributary is a lateral deltaic plain extending into a baymouth barrier, which separates the large lagoon system of Razelm-Sinoe, once open (PANIN, 1983), from the sea. The shelf is broadest in front of the delta and narrows to the south. The nearshore gradients to a 15-m depth along the Danube delta coast range between 0.003 and 0.01. The beach profile is generally multibarred (POSTOLACHE *et al.*, 1992).

The modern sediments on the northern sector of the coast consist of Danube-borne quartz sands containing about 70% silica (PANIN, 1989). The heavy mineral content is about 3%. Sands carried in littoral drift from the region north of the Danube delta have a higher silica content than the Danubian sediments (90% silica). The subaerial beach sediments are generally medium-fine sands with a median grain size, $d_{50} <$ 0.5 mm. In the offshore, well-sorted sands (75% sand) are found out to about the 10-m isobath (BONDAR *et al.*, 1973; RCMGG, 1995). The 10-m isobath also coincides approximately with the offshore limit of those sediments with a median grain size greater than 0.1 mm. Exceptions are a restricted area of low wave energy situated in the lee of Sulina jetties, and deltaic plain coast between Sacalin Island and Perisor (Figure 1), where this limit is found at depths less than 5 m. Shell debris increases the grain size locally, especially on the Razelm-Sinoe baymouth barrier beaches (GIOSAN, 1993).

The evolution of the Danube delta has been extensively studied by PANIN (1974, 1989) and PANIN *et al.* (1983). The delta development began during the Quaternary and it was strongly influenced by the sea-level changes during this period. During the Würm regression, the level of the Black Sea was about 100 m lower than today, favoring erosion of the Upper Pleistocene deposits. The delta formed during the succeeding transgression by an alternate channel extension process (WRIGHT, 1985). One to four distributaries were active, either alternately or contemporaneously, each building its own deltaic lobe. Of the three main active distributary lobes (Chilia, Sulina and Sfantu Gheorghe), the Chilia and a secondary delta on the south side of the Sfantu Gheorghe mouth are prograding. At Sfantu Gheorghe, the prograding section is protected by a barrier island, Sacalin. The Sulina lobe is continuously eroding, while the northern side of the Sfantu Gheorghe lobe appears to be in dynamic equilibrium. Farther south, the baymouth barrier beaches are retreating. The rate of retreat in all eroding sectors seems to be enhanced by the general decrease of the Danube sediment discharge during the last century, by the influence of river mouth jetties and harbor jetties, and by dredging practice (BONDAR *et al.*, 1992; RCMGG, 1994). Sand periodically dredged from the Sulina mouth bar has been disposed in relatively deep water offshore, where it seems unlikely to return to the littoral system (RCMGG, 1994).

Sea Level Variations

The long-term, relative sea-level rise has been estimated to 3.3 mm/year at Sulina and between 1.2 and 1.8 mm/year at Constantza (BONDAR cited by SPATARU, 1990). A neotectonic map of Romania (BANDRABUR *et al.*, 1971) shows the Danube delta subsiding at a rate of 1 to 2 mm/year. Both the compaction of deltaic sediments and regional tectonics would contribute to the long term sea level changes but details of these estimates were not readily available to resolve the differences.

The tide of the Black Sea along the Romanian coast is semidiurnal, with a range of 7 to 12 cm. It is negligible compared to other water-level fluctuations, such as seiches or storm surges, which can reach a maximum of 2 m height, and 1.2 to 1.5 m respectively (RCMGG, 1994). Other sea level fluctuations are due to changes in the water exchange through the Bosphorus strait and differences in precipitation and evaporation rates, as well as variations in the river discharge. In response to the variations in river discharge, the sea level fluctuates between 20 and 30 cm from season to season and about 20 cm from year to year (RCMGG, 1994).

River Discharge

The Danube provides 38% of the river water entering the Black Sea (GLASKOW, 1970). The Danube's annual discharge is highest from April to July. Between 1858 and 1988 the mean annual discharge was about 191 km^3, of which 63% entered the Black Sea through the Chilia distributary, 17% through the Sulina and 20% through the Sfantu Gheorghe (BONDAR *et al.*, 1992). The annual discharge increased from 178 km^3 in 1858 to 203 km^3 in 1988. The mean total sediment discharge of the Danube was about 52×10^6 metric tons per year between 1858 and 1988. This also showed a long-term trend, decreasing from 65×10^6 metric tons in 1858 to 38×10^6 metric tons in 1988 (BONDAR *et al.*, 1992). Fifty-five percent of the sediment discharge was delivered through the Chilia distributary, 21% through the Sulina and 23% through the Sfantu Gheorghe arm. A reduction of the total sediment discharge of between 25% to 30% was recorded after 1970, when the first of the Iron Gates dams was constructed in the Romanian-Yugoslavian sector of the Danube (RCMGG, 1994; POPA, 1992). The bed-load sediment discharge is reported to have a median grain size of between 0.1 and 0.5 mm, and its discharge has been estimated to account for 4.5% to 10% of the total sediment discharge (BONDAR *et al.*, 1973; HANCU *et al.*, 1992). The Chilia distributary discharges about 3×10^3 metric tons per year of bed-load sediment or between 57% and 65% of the Danube's total bed-load discharge. The Sulina's bedload discharge is between 0.85×10^6 and 1.3×10^6 metric tons per year (19% to 25% of the total), and the Sfantu Gheorghe's between 0.75×10^6 and 1×10^6 metric tons per year (19% to 21% of the total; BONDAR and HARABAGIU, 1992).

While the sediment discharge of the Danube decreased in the last century, mainly due to damming, the water discharge increased. The increase in water discharge can be attributed to climatic changes and, partly, to marsh reduction. The concurrent 25% to 30% reduction in sediment discharge was not as large as that in the Nile (98%; SESTINI, 1992) or Ebro (95%; JIMENEZ and SANCHEZ-ARCILLA, 1993), because of both increased channel erosion in the lower course of the river (MIHAILESCU, 1983; RCMGG, 1994) and artificial meander cut-offs in delta distributaries in the 1990s (RCMGG, 1994). Major rivers draining the Carpathian mountains downstream Iron Gates are also dammed, and their discharge is therefore insignificant. The decrease in the sediment discharge due to dams contributes to a total reduction of 40% in the annual total load since 1858.

Wind and Wave Regime

The average wind speed in the northwestern Black Sea is between 5 and 6.5 m/s (BULGAKOV *et al.*, 1992). The annual modal direction for onshore winds is from the northeast. During the summer months, however, the predominant direction is onshore from the south-southeast while it is from north-northeast in winter (DIACONU *et al.*, undated, as cited by

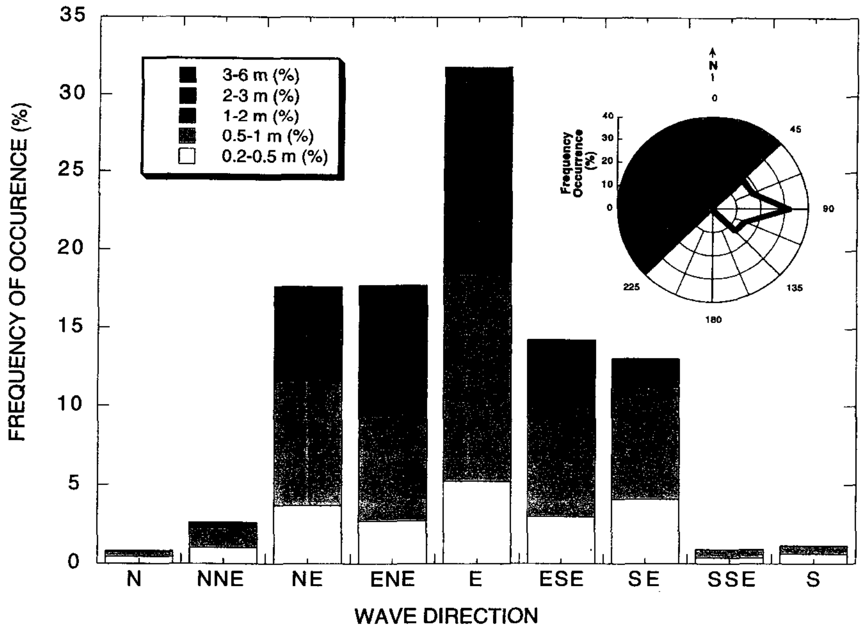

Figure 2. Frequency of occurrence of wave height as a function of approach direction at the coast. A wave rose is also shown for all waves available, along with the average orientation of the coast.

RCMGG, 1994). Because the Romanian coast is relatively short, the wind regime does not vary significantly along the coast, especially for the onshore winds (CIULACHE, 1993). Storms from the north and northeast are characterized by an average wind speed of 9.8 m/s and a duration ranging between 8 and 22 hours (DIACONU *et al.*, undated, as cited by RCMGG, 1994).

The wave regime was analyzed for this study based on wave observations made over a 10-year period between 1972 and 1981 at a depth of 11 m, offshore the southern town of Constantza (Figure 1; see "Methods"). Waves higher than 0.2 m (the lower limit of the wave height that was measurable using the available instrumentation) arrived at the coast from all offshore directions about 51% of the year (Figure 2). Of these, 60% to 85% are local wind waves, and 15–40% swells (DIACONU *et al.*, undated, as cited by RCMGG, 1994). The annual average significant wave height was 0.8 m, with a annual standard deviation of 1 m, and a mean period of 5 seconds.

Engineering Works

Construction of two jetties at the Sulina mouth began in 1856 to protect Sulina navigation channel against shoaling with littoral sediments (Figure 1). They were subsequently extended and now reach 8 km offshore. The jetties strongly affect the evolution of the beaches farther south, both by channeling the distributary sediment load offshore, and by intercepting the longshore drift of sand from the north (SPATARU, 1990; RCMGG, 1994). During the second half of the 19th Century, channels were cut to shorten the navigation route on the Sulina distributary. When this was done, the southern arm of Sfantu Gheorghe lost about 30% of its water discharge, and consequently its sediment transport capacity, in favor of the shortened arm of Sulina (SPATARU, 1990). Most of Sulina bed-load accumulates at the end of the jetties as a mouth bar, which is periodically dredged to maintain a channel depth of 8 m. The dredged sediments are discharged offshore, and thus are lost from the nearshore transport system (RCMGG, 1994). During the 1980's Sulina Harbor was extended inland and dredged sand was supplied to Sulina beach, situated just south of the jetties. Two groins were also built. Revetments were recently built along the coast between Sfantu Gheorghe and Sulina and along the southern barrier beaches in front of the Razelm-Sinoe lagoons (POSTOLACHE *et al.*, 1995). In order to further mitigate the beach erosion on these beaches, some Romanian hydrotechnical engineers have proposed to deviate part of the Sfantu Gheorghe distributary water and sediment load through a channel discharging south of Sacalin Island (Figure 1; HANCU *et al.*, 1992). Midia Harbor (Figure 1) is protected by jetties extending about 5 km offshore. These also restrict the amount of sand carried southward by redirecting it offshore.

Shoreline Dynamics

The northern part of the delta coast, which includes the Chilia delta, has been rapidly prograding in the last two centuries (PANIN, 1989; MIKHAILOVA, 1995). After construction on the Sulina jetties began in the mid-19th Century, the deltaic coast farther south was partly deprived of littoral sediment coming from northern Chilia coast. This degree of isolation increased in time with the extension of the jetties.

Beach profiles were surveyed with a theodolite or level on

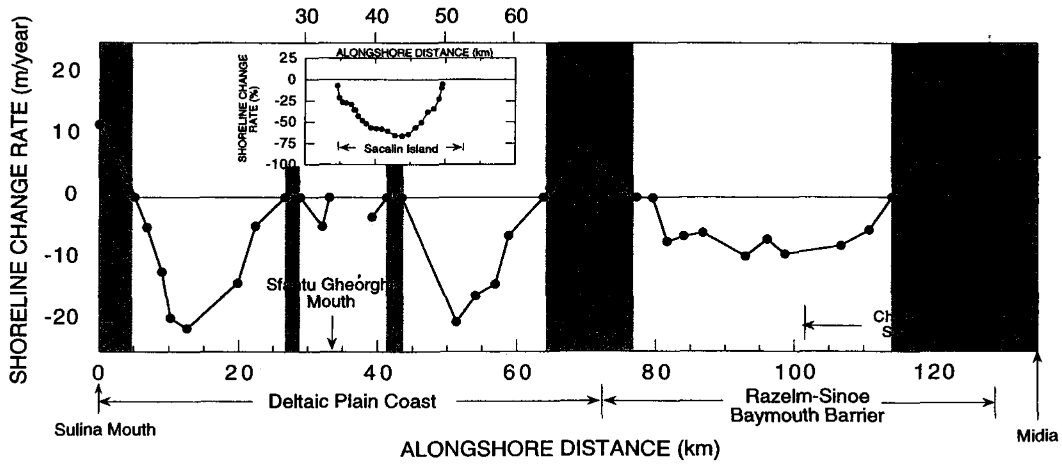

Figure 3. Rates of shoreline change on the Romanian Danube Delta coast south of Sulina and the adjacent baymouth barrier of Razelm-Sinoe, between 1962 and 1987 (with data published by Vespremeanu and Stefanescu, 1988), and between 1962 and 1993 for Sacalin barrier island (using data from Breier and Teodor, 1979 and RCMGG, 1994). Advancing coast sectors (see Figure 3) are colored in gray.

a network of landmarks along the delta coast south of Sulina, including one landmark on Sacalin Island. An initial network of 60 monuments was established in 1962. In 1982 only 19 landmarks were left, and another 100 landmarks were set in 1985. From these, 18 were integrated into the Romanian geodetic network (VESPREMEANU and STEFANESCU, 1988). The beach profile measurements were reduced to the national Black Sea vertical datum. Shoreline changes were analyzed by VESPREMEANU and STEFANESCU (1988; Figure 3) for the period between 1962 and 1987. The actual shoreline positions were not published, but only the calculated end-point shoreline change rates. The Romanian Marine Geology and Geoecology Institute (RCMGG) also made annual profiles after 1978 within the framework of the "Danube-Black Sea System Monitoring Program" (RCMGG, 1994).

The shoreline is retreating over almost the entire Danube delta coast situated south of Sulina mouth (Figure 3). The maximum retreat rate for the coast between Sulina and Sfantu Gheorghe is over 20 m/year about 15 km south of Sulina jetties. ALMAZOV *et al.* (1963) suggested the existence of an anticyclonal eddy attached to the south lee side of the jetties, which can be explained by the sheltering and diffraction of waves by the structures (KRAUS and HARIKAI, 1983). This eddy might induce an increase in the local divergence of the longshore sediment drift, therefore accelerating erosion. The existence of the divergence zone is recognized in sediment drift studies based on radioactive or fluorescent tracers (BONDAR and CRACIUN, 1970; DRAGOTA, 1973), in salinity distribution studies (BONDAR, 1964), and by physical modeling (SPATARU, 1971). Immediately south of Sulina jetties there is a local zone of shoreline progradation accompanied by intense shoaling of the submerged profile (BONDAR and HARABAGIU, 1992).

On the northern side of Sfantu Gheorghe lobe, the shoreline was slowly prograding until the late 1970's, apparently reaching a dynamic equilibrium afterwards. Sacalin barrier island is continually retreating with average rates greater than 20 m/year and locally over 60 m/year. On the deltaic mainland coast, there is intense progradation of a secondary delta in the shallow bay (about 1 m deep) behind Sacalin Island.

Farther south, the shoreline is generally retreating, except for a short sector where the shore orientation changes from approximately E–W to a NE–SW direction (Figure 1; between km. 65 and km. 75 on Figure 3), and immediately north of Midia harbor jetties. The submarine slope also shoals on both sides of the Midia structures (RCMGG, 1994).

Nearshore Processes Along Sacalin Barrier

BRATESCU (1912), BREIER and TEODOR (1979), VESPREMEANU (1983), BONDAR *et al.* (1984) and RCMGG (1994) analyzed the genesis and evolution of Sacalin Island (Figure 1). This barrier island formed in 1897 from an emergent bar (BRATESCU, 1912). Sediments discharged by the Sfantu Gheorghe distributary, combines with longshore drift from north, to accumulate as a bar at the mouth of Sfantu Gheorghe. JIANU and SELARIU (1970) suggested that mouth bar sands are transferred south during storms, contributing to a continual increase in the length of Sacalin Island. Successive maps and aerial photos show that the shoreline of the island has been retreating since 1911 at the same time it has been lengthening (Figure 4). The retreat is most intense midway along its length (RCMGG, 1994). The northern half was already connected to the mainland marshes in the 1970s due both to the island's retreat and to rapid progradation of a secondary delta of the Sfantu Gheorghe into the bay (Figure 4). Because the island's altitude is typically less than 1.5 m, its retreat is apparently controlled by overwash and breaching, as suggested by the successive breaches and washover fans which have occurred over the years following major storms (RCMGG, 1994). Any breaches were closed rapidly;

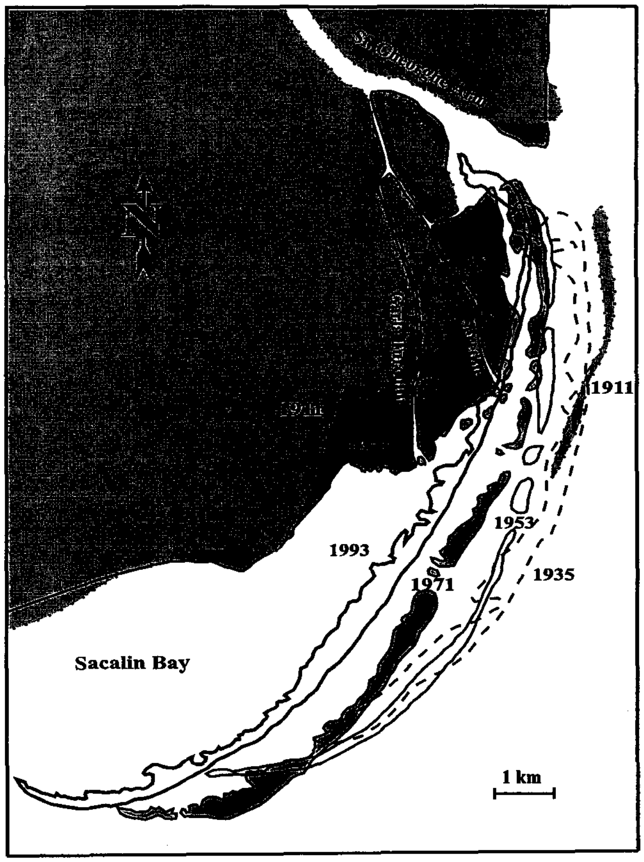

Figure 4. Consecutive positions of Sacalin barrier island (after Breier and Teodor; 1979, Gastescu, 1979; and RCMGG, 1994).

because the wind-induced flows between the lagoon and the sea are not strong enough to keep them open. The southern tip of the island recurves into the lagoon as governed by a wave refraction pattern typical for this type of setting (*e.g.* KANA, 1996), and also because the low relief beach at the tip evolves in an overwash mode (as conceptually described in KANA, 1996). The analysis of island evolution for the 1858–1968 period (BONDAR *et al.*, 1983) showed that the island platform built rapidly in an offshore direction between 1850 and 1923. This rate was reduced after 1923 leaving the profile unaltered below 10-m depth until 1968. Above this depth the bathymetric contours show a retreat for the same period. Consequently, the beach profile to a depth of 10 or 12 m has flattened while the island retreated. Comparison of bathymetric charts show that the island platform has been building in the longshore direction (JIANU and SELARIU, 1970). This process extends to a depth of about 12 m and it was uninterrupted though episodic, between 1858 and 1968 (BONDAR *et al.*, 1983).

In summary, offshore sediment transfer combined with overwash and breaching extract sediments from the Sacalin nearshore system. The first is responsible for the growth of the subaqueous island platform in both axial and offshore directions. Using the maps of BREIER and TEODOR (1979) and RCMGG (1994), the island shoreline changes for the 1962–1993 period were computed for this study (Figure 3). The long-term behavior of Sacalin was examined based on previously published island positions (Figure 4) for 1911, 1935, 1953 (BREIER and TEODOR, 1979), 1971 (GASTESCU, 1979) and 1993 (RCMGG, 1994). The results of this morphometric analysis remain somewhat provisional, given the fact that the accuracy of the maps earlier than 1971 cannot be estimated.

Longshore Sediment Transport

Sand accumulation on opposite sides of Sulina jetties and the longshore growth of Sacalin barrier island have been previously used as direct indicators of the longshore sediment transport direction and magnitude on the Danube delta coast. These studies indicated an extremely high net longshore transport. From north to south, the sediment drift is directed southward along Chilia lobe, shows a reversal south of Sulina jetties, and continues southward to Midia afterwards.

Shoreline changes also were used to estimate a net sediment transport of about 700,000 m^3/year southward along Chilia delta (SHUISKY, 1984). The southward drift assessed from the shoaling rates on the northern side of Sulina jetties can be anywhere between 1,100,000 and 1,900,000 m^3/year (BONDAR and HARABAGIU, 1992), since the area for which the rate of shoaling was calculated was not clearly specified.

The subaqueous shoaling rate of 500,000 m^3/year to 1,300,000 m^3/year (BONDAR and HARABAGIU, 1992) south of the jetties provided a direct estimate of the net longshore transport in the reversal zone south of Sulina. The natural shoaling in this area was overestimated because an unknown, but substantial amount of sand retrieved from Sulina Harbor, was discharged on the beach in the 1980s.

South of the reversal zone to Sfantu Gheorghe, the longshore drift was estimated at 700,000 m^3/year (RCMGG, 1994) based on an analysis of shoreline changes.

The southward growth of Sacalin's platform is also an indicator of the net longshore transport rate. BONDAR *et al.* (1983) estimated this shoaling, to a depth 20 m, at 1,760,000 m^3/year.

Farther south along Chituc Spit, BONDAR *et al.* (1980) estimated the longshore transport by using synoptic wind data to hindcast the wave climate. The calculated drift was directed southward at a rate of about 1,800,000 m^3/year down to the 25 m isobath, which was taken as the offshore boundary for calculation.

METHODS

Potential Longshore Sediment Transport Rate

Wave characteristics have been recorded at Constantza, in the southern part of the Romanian Black Sea coast, since 1964 by the Romanian Marine Sciences Research Institute. Significant wave height, mean period, and mean direction at 6-hour intervals over a 10-year period between 1972 and 1981 were used in the present study (Figure 2). The measurements involved visual observations of a buoy moored in a water depth of 11 m. The measured characteristics include mean

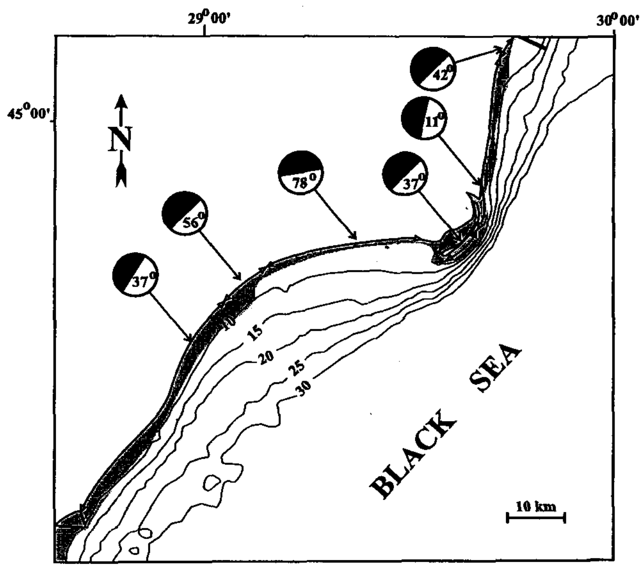

Figure 5. Bathymetry of the study area (depths in meters), with the average orientation of different regions used in computing the potential longshore sediment transport. The high-energy nearshore zone consisting of well-sorted sands (75% sand) is colored in gray.

wave height, period, and direction three times daily during the daylight. The wave direction is estimated visually, with an accuracy of about 20°. Gaps in the record due to periods of poor visibility were filled with values generated to be statistically consistent with observed record (KRAUS and HARIKAI, 1983). Wave data were sparse for other parts of the coast. Because the wind regime does not vary significantly along the relatively short coast, however, the wave climate at Constantza was assumed to represent that for the entire coast.

The bathymetry of Romanian coast (Figure 5) was obtained by digitizing 1:50,000 scale maps published by the Romanian Navy Hydrographic Service, based on their 1979 survey. The observed waves were then backward-refracted on the bathymetry around the point where they were measured using iteratively a wave transformation program provided by U.S. Army Corps of Engineers (RCPWAVE; EBERSOLE *et al.*, 1986), in an attempt to transform the wave data for deep-water conditions (−30 m). However, because the angle of approach is poorly resolved in the original wave data, the transformed data were not substantially different than the original measurements.

The potential longshore sediment transport was estimated using a nearshore sediment transport model based on the wave energy flux (NSTRAN; U.S. ARMY CORPS OF ENGINEERS, 1984). The constant k (usually taken as 0.77) describes the efficiency of the longshore component of wave energy flux in transporting sediments. Systematic measurements in other areas have shown that k is actually variable, dependent upon the nature of the breaking waves and the grain size (*e.g.* WANG *et al.*, 1998; WHITE and INMAN, 1989; DEAN, 1989). Herein the constant k was calibrated using sand budget computations for a single 12 km stretch of the Romanian coast as described in more detail below. An adjusted value (k = 0.35) was then applied to the entire coast. Both NSTRAN and RCPWAVE are components of the "Shoreline Modeling System" (SMS) standardized software collection created by the U.S. Army Corps of Engineers (HANSON and KRAUS, 1989: GRAVENS *et al.*, 1991).

The 140 km-long area extending from Sulina to Midia, was divided into six regions according to their average shoreline orientation (Figure 5) which is required as an input parameter by SMS. The 10-year wave time series was refracted on the grided bathymetry. This was done using RCPWAVE for each region at 1-km intervals and 500-m intervals in the offshore direction to the 30-m isobath. The RCPWAVE output (*i.e.* the wave parameters at breaking) was then inputted to NSTRAN which computed the potential net sediment transport rates along each region. The distribution of the calculated net potential transport for the entire study area was then assembled from the six regional net transport patterns. The distribution was then compared to the pattern of net transport derived from a sand budget.

Sediment Budget

A sand budget was the other method used to estimate the distribution of longshore sediment transport in the study area. The active beach volume changes for the budget were calculated based on shoreline change rates for the period between 1962 and 1987 published by VESPREMEANU and STEFANESCU, (1988; Figure 3). The volume changes were calculated individually for each stretch of the coast between two adjacent beach profiling stations. The distance between profiling stations varies between 1 and 10 km. The shoreline change data do not extend as far south as Midia Harbor: the southernmost observations are 14 km north of the harbor. The shoreline progradation rate was considered to be constant southward of the last measurement point and to have the same value as measured at that last transect. Although the measurement stations used for collecting the shoreline change data were widely spaced along the coast they are considered to represent well the shoreline behavior, being very similar to the estimates presented by others (PONS, 1992; SPATARU, 1992; GASTESCU, 1993).

The active beach, the longshore transport, and the river sediment input were assumed to be the only sources or sinks for sediments for the entire study area, with the exception of Sacalin Island. The above assumptions would not be valid along the barrier beach of Sacalin Island, since the cross-shore sedimentation by offshore loss (JIANU and SELARIU, 1970; BONDAR *et al.*, 1984) and secondarily by overwash and breaching (RCMGG, 1994) are likely to be important. Therefore, sand budgets were calculated separately for the coast segments situated north and south of the island.

The northern segment was taken between Sulina mouth and Sfantu Gheorghe mouth. The Sulina mouth jetties were considered to be impermeable to sediment transport because they extend almost to the estimated depth of closure (discussed below). Thus the northern lateral boundary for this segment was considered closed, while the southern one was left open. Based on riverine efflux studies (BONDAR, 1964), and geomorphic evolution (VESPREMEANU, 1983) of the Sfantu Gheorghe mouth, it is reasonable to assume that the sediment discharged by this distributary is directed largely to the south, so that there was no significant contribution from this source to the northern shoreline segment between Sulina and Sfantu Gheorghe.

The southern segment was taken on the deltaic mainland shore south of Sacalin Island down to Midia. The southern lateral boundary was assumed to be closed because the jetties protecting Midia Harbor intercept the longshore sediment transport. Apparently, little sand bypasses the harbor jetties since Mamaia beach situated to the south of Midia has a chronic sand deficit. The northern boundary of this cell was left open. Net longshore transport patterns for each segments were derived from the volume calculated changes by integrating them starting at the closed boundaries.

Beach volume changes were calculated differently depending on whether the shoreline was advancing or retreating over the time period considered. During the formation of a delta, both the shoreline and the subaqueous delta advance at the same rate (*i.e.* long term beach profile is invariant; PELNARD-CONSIDERE, 1956; HANSON and KRAUS, 1989). In this situation a "one-line" model which takes the beach profile as invariant is used in the calculation of sand volumes. The beach volume change (ΔV) for the accreting sectors is thus computed as (INMAN and DOLAN, 1989):

$$\Delta V = \Delta x \cdot Z \cdot L \ (m^3)$$

based on the average shoreline advance of each sector (Δx), the vertical distance over which the erosion occurs (Z), and the sector length (L). Z was taken from the top of the berm to the depth of closure.

The berm elevation was determined from available beach profiles to be approximately 0.5 m. Because suitable submerged beach profile measurement series were unavailable for the Romanian coast, the depth of closure along the coast was estimated using a sedimentologic proxy: the offshore limit between well-sorted sands (>75% sand) and sediments with a higher fine fraction contribution (>25% silt and/or clay-sized material). A detailed sedimentological map of the Romanian shelf was used for this purpose (RCMGG, 1995). The closure depth determined in this way was never far from the 10-m isobath offshore of open beaches, but decreased to values less than 5 m in the lee of Sulina jetties, and of Sacalin barrier island (Figure 5). This value for the closure depth was consistent with other estimates appropriate to the open coast. Based on annual statistics of the wave climate for the 1972–1981 period, HALERMEIER'S method[1] (1981) indicates that the annual depth of closure varies between 6 and 12 m. Previous studies of the long-term nearshore changes on Sfantu Gheorghe beach and along Sacalin Island also indicated a closure depth between 10 and 12 m (JIANU and SELARIU, 1970; BONDAR *et al.*, 1984). It was reasonable to use the "one-line" model for the accreting sector of the shoreline south of Sulina jetties which seems to conserve an equilibrium during its advance (GASTESCU, 1993), as well as for the other advancing shoreline sectors.

When a deltaic shoreline is retreating, however, as is the case on most of the Danube delta coast under study, the shoreline tends to retreat more rapidly than the subaqueous delta (REFAAT and TSUCHIYA, 1991). This behavior probably is due to the higher erosion rates in the surf zone compared to farther offshore following a decrease in the river sediment discharge, which must occur to maintain the potential longshore sediment transport rate (REFAAT and TSUCHIYA, 1991). Thus a single, equilibrium beach profile is not maintained during the delta reduction process, but the slope of the profile becomes more gradual. This was found to occur on the Ebro delta over a scale of several years (JIMENEZ and SANCHEZ-ARCILLA, 1993). For calculating sand budgets in this situation it seemed more appropriate to compute the volume changes using a wedge-shaped erosional prism. To account for the wedge shaped profile change of the retreating sectors the above formula becomes:

$$\Delta V = \Delta x \cdot Z \cdot L/2 \ (m^3)$$

where Δx is the shoreline retreat.

RESULTS

The trends in the net longshore transport provided by the sediment budget compared favorably to that calculated by the wave energy flux method. The location of the main convergence and divergence points coincide fairly well (Figure 6). However, when the customary efficiency factor $k = 0.77$ is used the magnitude of the potential transport is unreasonably high. Therefore, the magnitude difference between the two longshore transport models was adjusted by calibrating the potential transport after the budget-derived transport. For calibration, the longshore transport rates on a calibration area (*i.e.* the most stable coastal stretch situated between km 20 and km 32, north of Sfantu Gheorghe mouth where the net transport was approximately constant) were averaged by integration. The magnitude of the potential transport for the same coastal stretch was then equaled to this average, and a value of 0.35 was calculated for k by solving the inverse problem. This adjusted value of k was then applied to calculate the potential transport on the entire coast. The similarity between the potential transport magnitudes and the magnitudes of budget-based longshore transport, outside the calibration area, was considered as a proof for the correct assessment of k.

The net longshore sediment transport along the entire studied coast is high on average, mainly as a result of the prevailing E–NE waves superimposed on NNE–SSE general orientation of the coast. The potential sediment transport to the south is one order of magnitude higher than the net transport to the north in all cases but downdrift Sulina jetties. Therefore the longshore transport is almost unidirectional southwardly all year long. These results, however, are consistent with previous estimates of the longshore transport

[1] The approximate solution for Halermeier's depth of closure d_c is: $d_c = 2H_s + 11\sigma$, where H_s is the average annual significant wave height and σ is the annual standard deviation of significant wave height.

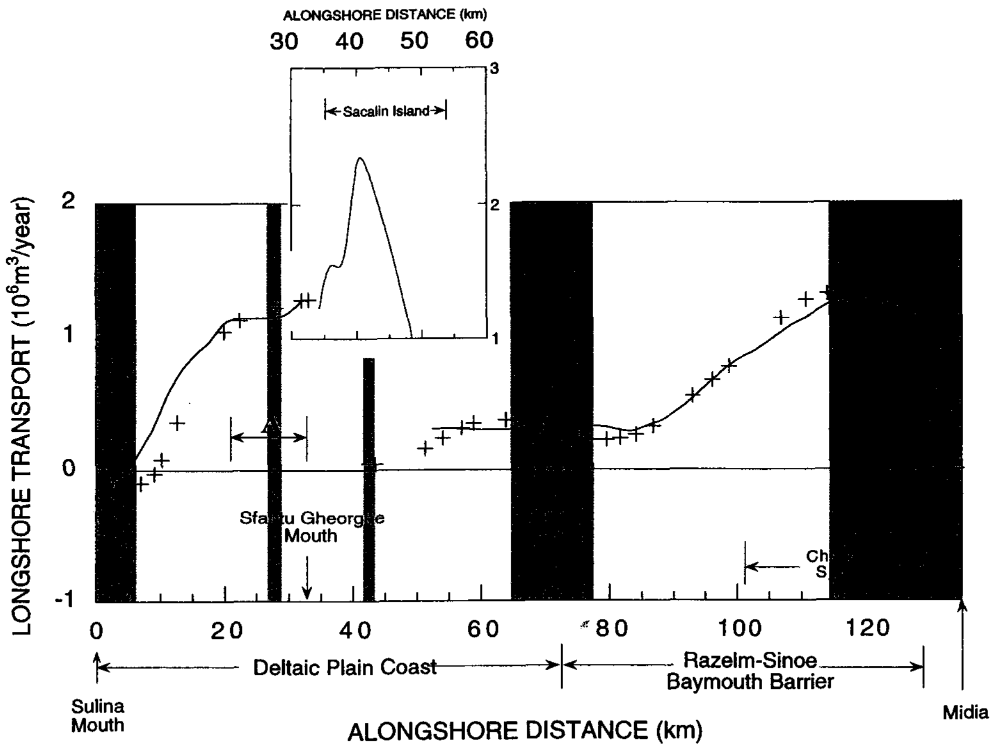

Figure 6. Pattern of net longshore sediment transport along the Romanian Danube Delta coast south of Sulina and the adjacent baymouth barrier of Razelm-Sinoe. The budget-derived sediment transport is represented by crosses while the potential transport is shown as a continuous line. The efficiency of the longshore component of wave energy flux in transporting sediments was calibrated along the stretch A (see text) to k = 0.35. Advancing coast sectors (see Figure 3) are gray-colored.

rates, as discussed earlier, and similar to those found on other deltaic coasts.

The Coast from Sulina to Sfantu Gheorghe

From Sulina to Sfantu Gheorghe, the resulting net sediment transport scheme was basically made up of two cells (Figures 6 and 7). The two-cell pattern is the result of the sheltering of waves coming from the NE quadrant, and diffraction around the jetties. One cell is directly south of the Sulina jetties. The net transport within this cell is directed northwardly with an average rate of 70,000 m^3/year. This magnitude of the sediment transport seemed inadequate to explain the shoaling rate of at least 500,000 m^3/year south of Sulina jetties (BONDAR *et al.,* 1992). Presumably, the discrepancy is due to the artificial nourishment of the beach with an unknown quantity of sand.

The second cell is longer and extends to the Sfantu Gheorghe. In this cell, the net transport is southerly at an average rate of 900,000 m^3/year. It increased from zero at the nodal point, up to 1,250,000 m^3/year, remaining fairly constant to the cell end, at Sfantu Gheorghe (Figure 6). The sediment transport rate increases to the south as the sheltering effect of Sulina jetties vanishes and the wave angle of attack increases due to a progressively greater gradient of the submerged beach to the south (Figure 5).

The uncertainty in wave data (especially of the direction estimates), poor performance of the wave refraction model adjacent to jetties, and the corrupted sand budget due to beach renourishment, all combine in creating differences between budget-derived and potential sediment transport patterns.

The Sacalin Island

Sacalin Island has periodically increased in length to the south, at rates up to 250 m/year, the rate estimated in this study for the period between 1911 and 1935. The island reached a maximum average width of about 800 m in 1940's (BONDAR *et al.,* 1983). Our estimates show that after 1960 the average width stabilized at about 200 m. The barrier island rolled landward at an accelerated rate after 1970 (Figure 4), possibly as a consequence of the decrease in Danube sediment discharge.

Between 1962 and 1993, Sacalin Island shoreline receded everywhere, reaching the highest retreat rate on the Danube delta coast (over 60 m/year) at the island's center (Figure 3). Consequently, the island convexity decreased (Figure 4). It was not possible to compute a sediment budget for Sacalin Island because measurements of the submerged beach profile were not available, and moreover, a sediment budget along the island will be strongly affected by offshore and washover

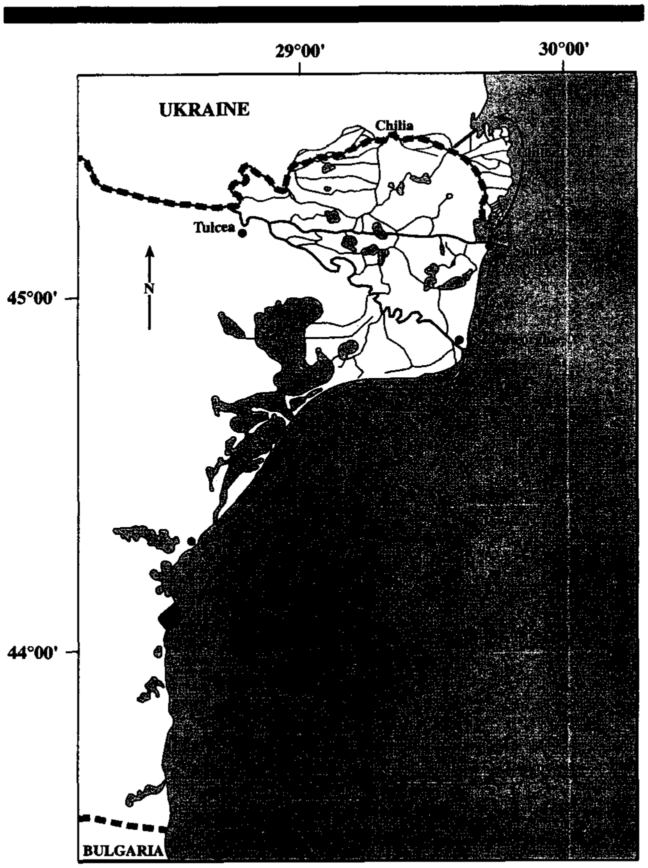

Figure 7. Longshore sediment transport model for the Danube delta coast (the transport along Chilia lobe is from Shuisky, 1984). Transport rates are in 10^3 m^3/year.

losses. However, the pattern of potential longshore transport was estimated using the same value for k (*i.e.* 0.35) as for the entire study area. The calculated net transport directed to the south with an average magnitude of about 1,720,000 m^3/year. This was, not unexpectedly, the highest figure on the entire Danube delta coast (Figure 7). The average shoreline orientation at Sacalin Island results in a high angle of wave attack, and the steep nearshore gradient minimizes wave refraction. The transport increased from about 1,270,000 m^3/year south of the Sfantu Gheorghe mouth to about 2,350,000 m^3/year in the island median section (Figure 6). For the southern half of the island, the transport decreased to 1,000,000 m^3/year. As the longshore transport decreases the southern half of the island should have been accreting but the shoreline retreated instead (Figure 3). Therefore, the shoreline variation must have been controlled by mechanisms other than the longshore sediment transport. Overwash, breaching (RCMGG, 1994), and offshore sediment transport during storms are all active processes here (BONDAR *et al.*, 1983 and BONDAR *et al.*, 1984). They are likely to have been responsible for the overall recession of the coast in the southern part of the Sacalin Island. The northern half of the island was wider and had foredunes which were about 4 to 5 m in height during the 1960s but which gradually decreased to about 2 m at present (RCMGG, 1994). Both the increased island width and the high foredunes would inhibit cross-island sand transport. The southern half of the island was narrower with a altitude of between only 0.5 and 1 m. Therefore this part of the island was more likely to be overtopped and breached during storms.

There is a convergence in net potential transport of about 700,000 m^3/year of sand between the southern tip of the Sacalin Island and the mainland (Figure 6). This amount of sand was apparently not transported farther south along the coast but accumulated on the island platform. BONDAR *et al.*, (1983) estimated the shoaling rate to a depth of 20 m to be 1,760,000 m^3/year between 1858 and 1968.

The Coast South of Sacalin Island

The net transport continued to have a southwardly general direction south of Sacalin Island (Figures 6 and 7). The pattern of the net transport calculated from the sand budget is similar to the pattern of the potential transport. Both show an increasing rate between km. 85 and 115 and a maximum value at km. 115.

On the deltaic plain coast southwest of Sacalin, the net longshore transport was directed southwestwardly at an average rate of about 310,000 m^3/year. A decrease in the transport to about 250,000 m^3/year was recorded at the root of the Razelm-Sinoe baymouth barrier (km. 72), where the coast orientation changes rather abruptly. The average rate of the net transport south of this convergence zone to Midia was about 920,000 m^3/year (Figure 7). The rate increased from 250,000 to a maximum of 1,300,000 m^3/year on the northern Chituc spit and decreased afterwards to 900,000 m^3/year at Midia (Figure 6).

A decrease in the potential transport rate between km 78 and km 85 indicated that the shoreline in that zone should have been advancing. An advance is shown by shoreline change data (Figure 6), but it is underestimated in the potential calculation both in the magnitude of the accretion and in the alongshore extension. This may be due to the uncertainties in the wave data as well as bathymetry.

DISCUSSION

The Chilia lobe is the only part of the Danube delta that is significantly prograding. The Sfantu Gheorghe distributary is in equilibrium on its northern side, progradation being active in a secondary delta behind Sacalin Island. The earlier lobe of Sulina continues to be reworked. It is likely that the erosion has been accelerated by dredging and the construction of jetties. The Sulina jetties further increase the imbalance in the sediment budget south of Sulina since no sand appears to be transferred by nearshore circulation from the Chilia lobe.

The coast between Sulina and Midia has retreated at high rates under the influence of a reduced river sediment input, and an intense longshore sediment transport due to the acute angle of wave attack. Since this part of the coast is closed at both its north and south ends by impermeable structures, shoreline changes were due to the longshore transport which redistributed sand from one area to another. Overwash and breaching appear to be important for the Sacalin barrier island, and potentially important for the narrow segments of the Razelm-Sinoe barrier. Sediment transfer to the offshore is probably active on along Sacalin, and is also induced by the jetties at Midia as evidenced by active deposition (RCMGG, 1994). The decrease in Danube sediment discharge after 1970 has caused an intensification of coast erosion, most evident on the northern side of Sfantu Gheorghe mouth and on Sacalin Island. At Sfantu Gheorghe the beach has stopped prograding and the shoreline retreat on Sacalin Island has intensified.

About 800,000 m^3/year of beach-quality sand (*i.e.* with a median size $M_d > 0.1$ mm) are lost from the nearshore system by maintenance dredging of Sulina distributary mouth. If it would be bypassed to the south of the reversal zone adjacent to the jetties this amount could reduce significantly the shoreline erosion to the Sfantu Gheorghe mouth. The zone of reversed sediment transport is responsible for trapping sand in the lee side of the Sulina jetties, increasing downdrift beach starvation.

The Sfantu Gheorghe distributary also discharges about 800,000 m^3/year of beach-quality sand. The potential sediment transport calculations indicate that the average rate of beach retreat on northern Sacalin, which was about 35 m/year, would more than double if this sediment input were to disappear. The sand passing the southern tip of Sacalin Island contributes to construction of the island platform. It is not a major sediment source for the beaches farther south because the shoreline orientation changes abruptly. Continued retreat of the island will probably enhance bypassing of sediments to the south.

Southwest of Sacalin, the coast is sheltered from northwesterly waves by the Sacalin Island and its subaqueous platform. Farther along the coast at Perisor, a change in orientation from E–W to N–S causes a convergence of the longshore transport, and thus beach accretion. The accretionary sector acts as a buffer for the sand transport farther south, further increasing sand starvation of beaches. The proposed channel to deviate some of the Sfantu Gheorghe distributary discharge south of Sacalin, as a solution to reduce the erosion, would probably cause the shoreline to advance locally at Perisor, but the Sacalin beach would have to compensate the loss via erosion to fuel the potential longshore transport. The beach of the barrier island, which already has the highest shoreline retreat rate on the Romanian coast, would became further starved for sand, endangering the rich Sacalin bay wildlife habitat.

The area with highest potential risk is the narrow barrier in the front of the Razelm-Sinoe lagoon system, even though the sand accumulation zone updrift of the Midia jetties may eventually provide some positive effects on a longer time scale. On the other hand, the sand trapped updrift of Midia starves the southern Romanian coast where most of the public beaches and tourist amenities have been developed.

CONCLUSIONS

Sediment transport is extremely intense along the Danube delta coast and along the lagoon system associated to it. Most of the delta coast is eroding, particularly its southern part (*i.e.* Sulina and Sfantu Gheorghe lobes). This is due to the southwesterly orientation of the southern half of the deltaic bulge which enhances the wave angle of attack and favors a unidirectional sediment transport to the south-southwest. The intensity of the sediment transport is somewhat tempered by a relatively low-energy wave climate.

The pattern of the net longshore sediment transport is controlled by the offshore bathymetry and by obstacles which obstruct the surf zone along the coast. These include jetties built at Sulina mouth and at Midia. The intensification of beach erosion due to river damming and other anthropic activities in a such intense sediment transport environment underlines the necessity for a better strategy regarding the management of this ecologically and touristically important area.

Increased coverage and accuracy of wave measurements would probably provide the greatest improvement in future studies. Three new gages are planned to be installed along the coast. At least one gauge should be situated between Sacalin Island and Midia where the shoreline orientation changes abruptly. For the highly active Danube delta coast, monitoring would include aerial photography of the area at least once a year; beach profiling to beyond the depth of closure on more closely spaced benchmarks, at least twice a year in order to estimate both the annual and seasonal variations; and bathymetric surveys for the highly dynamic areas such as the Sulina and Sfantu Gheorghe mouths, and Sacalin Island at least once per decade. A potentially promising method for estimating sand transport to be used in the model calibration would be the monitoring of the shoaling upstream Midia jetties, a site which is far enough from Danube distributaries mouths and not influenced by their sediment discharge.

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□ REZUMAT □

Obiectivul acestui studiu a fost evaluarea cantitativă a transportului de sedimente în lungul țărmului Deltei Dunării. Pe baza ratei de retragere sau avansare a liniei țărmului, a fost construită o balanță sedimentară pentru partea românească a țărmului Deltei. Pentru a transforma această rată în volum de sedimente erodate sau depuse s-a folosit un model hibrid, care consideră că zonele de retragere a țărmului se comportă diferit fată de cele de avansare. Pentru zonele erozive volumul de sedimente erodate de pe plajă ia forma unei "pene" care se subtiază spre larg. Pe de altă parte, s-a considerat că depunerea sedimentelor în zonele de avansare se face în cantitate egal distribuită pană la "adâncimea de închidere". "Adâncimea de închidere" a profilului subacvactic al unei plăji este definită ca fiind adâncimea la care acest profil încetează să mai sufere schimbări semnificative cantitativ în decursul unui an. Pentru țărmul românesc adâncimea de închidere este de aproximativ 9 metri. Transportul net de sedimente în lungul țărmului a fost calculat prin integrare, pornind de la conditii de limită laterală cunoscute. In final, acesta a fost comparat cu transportul potential, calculat cu ajutorul metodei transferului de flux energetic produs de valuri. Pentru modelarea transportului potential au fost folosite măsuratori de valuri efectuate între 1972 si 1981 la Constanta. Rezultatele celor două metode folosite coincid ca alură generală, fiind în limitele acestui tip de modelare. Ele arată că in timp ce delta Chiliei de pe teritoriul ucrainean îsi poate mentine avansarea spre larg deoarece bratul Chilia varsă cele mai multe sedimente in mare, portiunea românească a deltei, care primeste o cantitate redusă de sedimente dunărene, este supusă unui proces general de retragere. Aceasta se datorează în principal eroziunii provocate de catre valurile care se apropie oblic de țărm, producând un transport de sedimente foarte intens în lungul țărmului, cu directia generală spre sud. Delta inactivată a Sulinei continuă să se retragă. Jetelele construite la gura Sulinei afectează negativ coasta adiacentă spre sud, până la Sfantu Gheorghe. Sedimentele dragate de pe bara Sulina sunt deversate în larg, de unde nu mai pot fi remobilizate de către valuri pentru a fi transportate spre mal. Actuala deltă Sfantu Gheorghe progradează doar ca o deltă secundară în spatele Sacalinului. Insula Sacalin se retrage continuu sub puternica actinue erozivă a valurilor de furtună. In ultimele două decenii ritmul retragerii insulei s-a accelerat ca urmare a scăderii generale a sedimentelor vărsate în mare de catre Dunăre. Plajele barieră ce protejează complexul lagunar Razelm-Sinoe sunt foarte vulnerabile la spărturi, deoarece fluxul de sedimente care le alimenteaza este captat mai la nord, ca urmare a situatiei batimetrice din zona Sacalin-Perisor.