LONGSHORE SEDIMENT TRANSPORT PATTERN ALONG ROMANIAN DANUBE DELTA COAST

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Abstract. The paper presents the littoral sediment drift patterns along the Romanian Danube Delta coast. Using sand budget techniques and simulations with the "Shore Modelling System" software package of U.S.Army Corps of Engineers the longshore sediment transport was computed for each of the six sections taken into consideration within the Danube Delta coast zone (about 140 Km-long). The current state of the beach dynamics along the coast of the Delta are presented herein and predictive observations are made. Some actions are proposed to be taken in order to improve the monitoring of the Romanian Black Sea coast zone.

Key words: littoral sediments, sediment transport, simulation, coast zone, Black Sea

INTRODUCTION

Many deltas around the world have been experiencing a drastic change in their evolution due to anthropogenic alteration of both water and sediment discharge, coupled with vigorous longshore sediment transport. In the case of Danube delta, coastal erosion is threatening the ecosystem of wetlands, and coastal lakes. Furthermore the chronic sand deficit extends downstream of the delta coast, negatively affecting the important tourist-economy of the seaside resorts in southern sector of the Romanian Black Sea shore. Several factors have been identified to explain the recessional behaviour of Danube delta: (1) alternate channel switching which diverts most of the river sediment discharge to a single distributary starving the earlier built lobes; (2) general decrease in the river sediment discharge due to damming, dredging and agricultural practices in the Danube drainage basin; (3) engineering structures which disrupt the longshore sediment transport pattern; and (4) relative sea level rise. The tidal processes are not important since the mouth of the Danube is a microtidal environment.

This situation is not unique but also found in other microtidal deltaic coasts like those of 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 and other river control structures in the drainage basin, dredging along the river, the entrapment of water and sediments in the drainage basin and deltaic plain for agricultural purposes, the decrease in the rainfall pattern, have been variously cited as important factors in decreasing the rivers sediment discharge and furthermore favouring the change from a general progradational character of a delta into a recessional one. The river sediment discharge have been reduced 95% from the total load in the Ebro case (Palanques and Guillen, 1995), and 98% for the Nile (Sestini, 1992), even though in some places, like the Ebro extensive agriculture and deforestation have had contrary effects (Palanques and Guillen, 1995). At the same time the acute orientation to the principal wave direction of some deltaic coastal segments tend to produce intense longshore sediment transport. This is the case of Nile delta coast where net longshore sediment transport rates up to 1,200,000 m^3/year were estimated (Quelennic and Manohar, 1997), or Volturno, 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 analyse the current behaviour of the Romanian Danube delta coast. We will show the importance of the wave induced longshore sediment transport and anthropogenically modified by engineering structures in controlling shoreline dynamics along the Danube deltaic coast partially inactivated by alternate channel switching. The energetic wave regime in the caused by the preponderance of local waves due to relatively short fetches, by the high angle of wave attack, and by the ineffective refraction on a relatively steep nearshore.

STUDY AREA

Geological Setting

The Romanian Black Sea coast (Fig.1) stretches over 245 km from the Chilia distributary of the Danube (45°12' N, 29°40' E) at the Romanian-Ukraine border to the town of Vama Veche (43°44' N, 28°35' E) at the border with Bulgaria. The Romanian coast can be divided using geographic and geomorphic criteria into a northern unit and a southern unit (Panin et al., 1979-1994). The northern unit is the low-relief Danube delta coastal zone while the southern unit is characterised by eroding cliffs and loess, protected in places by narrow beaches (Charlier and de Julio, 1985; Panin, 1979-1994).

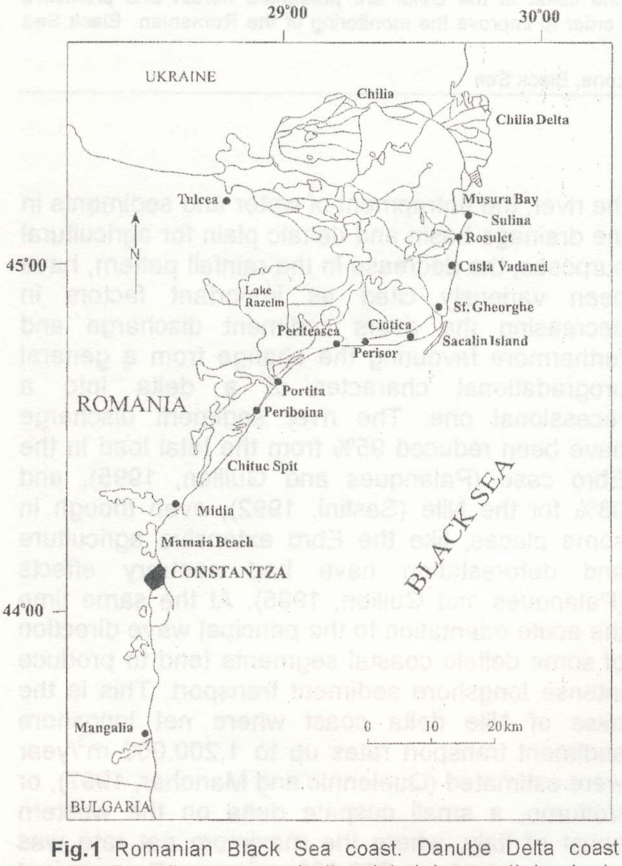

Fig.1 Romanian Black Sea coast. Danube Delta coast (including the adjacent, genetically related, baymouth barrier in front of Razelm-Sinoe lagoons) extends from Chilia to Midia.

The Romanian deltaic coast extends from the border with Ukraine to Midia in the south. The stretch of shoreline which includes Musura bay in the north, and extends to the southernmost distributary of the Danube, Sfântu Gheorghe, with the adjacent Sakhalin barrier island (Fig.1) constitutes the major contact of the Danube delta with the Black Sea. Reworked deltaic sands along the shore have built a coastal barrier complex from Sfântu Gheorghe to Midia. The barrier complex consists mainly of a baymouth barrier which separates the large lagoon complex of Razim-Sinoe, once open (Panin, 1983), from the sea. The shelf is broadest in the front of Danube delta and narrows to the south. The nearshore gradients to a 12-15 m depth along the Danube delta coast, range between 0.003 and 0.01, with the steepest slopes along the Sakhalin barrier island (Panin, 1985). 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 (about 70% silica; Panin, 1989). The heavy mineral content is about 3%. Sands carried by the littoral drift from the region north of Danube delta have higher silica content than the Danubian sediments (90%). The subaerial beach sediments are generally medium-fine sands ($d_{50}<0.5$ mm). Enlarged contribution of shell detritus increases the grain size locally, especially on the Razim-Sinoe barrier complex beaches (Panin et al., 1979-1994; Giosan, 1993).

The evolution of the Danube delta has been extensively studied by Panin (1974, 1989) and Panin et al. (1983). The delta development has begun during the Quaternary and it was strongly influenced by the sea-level changes during this period. During the Würm regression, the level of Black Sea was about 100 m lower than today. This position favoured the 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 alternately or contemporaneously active, each building their own deltaic lobes. Today there are three main active distributaries: Chilia, Sulina and Sfântu Gheorghe. Only Chilia, the northernmost distributary lobe, and the secondary delta of Sfântu Gheorghe arm, which has been built in a quiescent environment behind Sakhalin Island, are prograding. Almost all the other coastal sectors are retreating. The rate of retreat seems to be enhanced by the influence of the recent coastal engineering structures (Panin et al., 1979-1994), and by the general decrease of the Danube sediment discharge during the last century (Panin et al., 1979-1994; Bondar et al., 1992).

Sea Level Variations

The long term sea level change estimates indicate a fall of-2.5 mm/year at Varna, Bulgaria in the southern part the coast, while the level rises in the northern segment with rates of 1.2-1.8 mm/year at Constantza, and 3.3 mm/year at Sulina (Bondar cited by Spătaru, 1990; Gâstescu and

Driga, 1986). The Danube delta subsides with 1.3-2 mm/year, due to the compaction of deltaic sediments and regional tectonics. The tide of the Black Sea along the Romanian coast is semidiurnal, with a range of 7 to 12 cm. It has an unnoticeable effect when compared with other deformational fluctuations, such as seiches or storm surges which can reach a maximum of 2 m height, and 1.2 to 1.5 m respectively (Bondar, 1972; Panin et al., 1979-1994). Other important mean sea level fluctuations with multiannual and seasonal cyclicity are due to river discharge, changes in the water exchange through the Bosphorus straight, and precipitation/evaporation variations.

River Discharge

The most significant factor affecting the hydrologic budget of the Black Sea is the seasonal variation of river discharge. The Danube provides 38% of the river water entering the Black Sea (Glaskow, 1970). Other important rivers in terms of their water discharge are Dniepr, Southern Bug, and Dniestr. Danube's annual discharge is highest from April to July. In response to the variation in river discharge, the sea level fluctuates between 20 and 30 cm from season to season and about 20 cm from year to year (Bondar, 1972). Between 1858 and 1988 the Danube discharged annually about 191 km^3 of water, of which 63% was discharged through the Chilia distributary, 17% through the Sulina distributary and 20% through the Sfântu Gheorghe distributary (Bondar et al., 1992). The Danube water discharge increased from 178 km^3 in 1858 to 203 km^3 in 1988. The mean total sediment discharge of the Danube was about $52x10^6$ metric tons per year between 1858 and 1988 (Bondar et al., 1992). The sediment discharge in 1858 was $65x10^6$ metric tons, but only $38x10^6$ metric tons in 1988 (Bondar et al., 1992). This discharge was distributed 55% to the Chilia, 21% to the Sulina and 23% to the Sfântu Gheorghe arm. About 25-30% reduction of the total sediment discharge has been recorded after 1970 when the first Iron Gates dam was closed in the Romanian-Yugoslavian sector of Danube (Panin et al., 1979-1994; Popa, 1992). The bed-load sediment discharge, that has a median grain size between 0.1-0.5 mm, has been estimated to be between 4.5% and 19% of the total sediment discharge. Today, the Chilia distributary discharges about $3x10^6$ metric tons/year bed-load sediments (between 57% and 65% of Danube's total bed-load discharge), Sulina about $0.85\text{-}1.3x10^6$ metric tons/year (between 18.5% and 24.5% of the total discharge), and Sfântu Gheorghe about $0.75\text{-}1x10^6$ metric tons/year (between 19% and 20.5% of the total discharge; Bondar, 1972; Bondar and Harabagiu, 1992). It can be noticed from above data that while Danube sediment discharge decreased in the last century mainly due to damming, the water discharge increased. Also the 25-30% sediment discharge reduction after Danube damming was not as extreme as in the case of the Nile (98%; Sestini, 1992) or Ebro (95%; Jimenez and Sanchez-Arcilla, 1993), but added to the previous regressive trend, it amounts to 58% of the total load. The increase in water discharge can be attributed to climatic changes, and partly after damming to marsh reduction. The Iron Gates dams (Iron Gates I and Iron Gates II) were closed in 1970's in the upper sector of Danube lower course. Major rivers draining the Carpathian and Balkan mountains are dammed, and discharge is therefore insignificant. The relatively small reduction in the sediment discharge after damming, was due to increased erosion of the river bottom and islets in the lower course of the river (Panin, 1979-1994; Mihailescu, 1983), and to meander cut-offs in 1990's, along the distributaries in delta area (Panin, 1979-1994).

Wind And Wave Regime

The average wind speed in the northwestern Black Sea is between 6.5 and 5 m/s (Bulgakov et al., 1992). The predominant wind directions during the year, as they were measured at meteorological stations on the coast, are from the north, west and south (Ciulache, 1993). The prevalent direction for the onshore blowing winds is from Northeast. During the summer months, however, the predominant direction is onshore from the south-Southeast (Diaconu et al., undated, as cited by Panin et al., 1979-1994). Because the Romanian sector is relatively short, the wind regime does not vary significantly along the coast especially for the onshore winds (Ciulache, 1993). Storms are prevalent from the north and Northeast, with an average wind speed of 9.8 m/s and a duration ranging between 8 to 22 hours (Diaconu et al., undated, as cited by Panin et al, 1979-1994).

Waves higher than 0.2 m occur about 50% of the year; 60-85% of them are local wind waves, and 15-40% swells (Bondar, 1972). The wave regime was analysed for this study based on wave observation made over a 10-year period between 1972 and 1981 at a depth of 11m, offshore the southern town of Constantza (see "Methods"). We found that 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 (Fig.2). The annual average significant wave height was 0.8 m, with a mean period of 5 seconds (Fig.3). Most waves arrived from the NE-SE quadrant, the predominant direction (about 30% of total waves) and energy flux being from E. The waves arriving from NE-ENE sectors occurred more frequently and their mean energy flux was higher than those from ESE-SE sectors. Nearshore wave climate is controlled by the beach slope, thus implicitly by the shelf width which narrows southward to Sfântu Gheorghe mouth, and widens farther south (see Fig.7). The strongest wave activity is expected along Sakhalin island, due to poor refraction and wave shoaling on the steep beach.

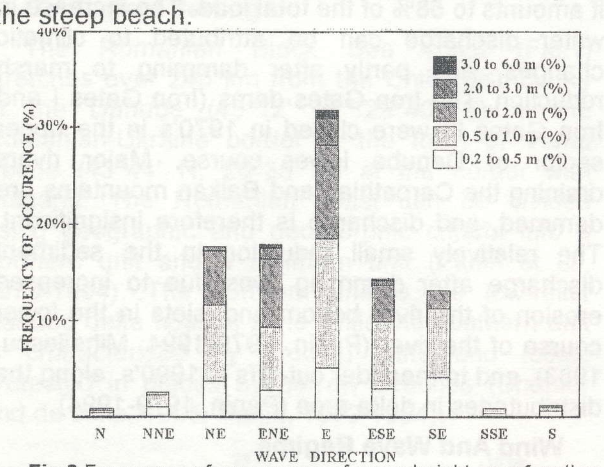

Fig.2 Frequency of occurrence of wave height as a function of their direction of approach to the coast.

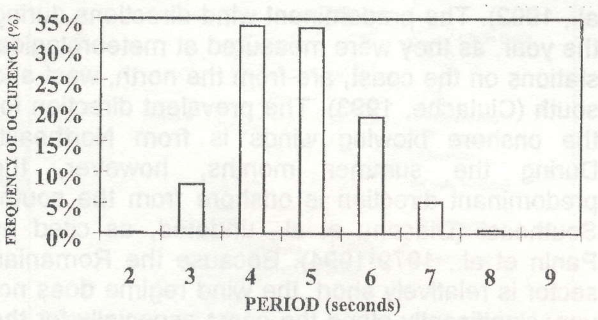

Fig.3 Frequency of occurrence of wave period

Engineering Works

Two jetties started to be built at the Sulina mouth (Fig.1) in 1856 and now extend as far as 8 km offshore. These jetties were built to protect Sulina navigation channel against shoaling with sediments drifting from the north. The Sulina jetties strongly affect the evolution of the beaches farther south, by discharging the distributary sediment load offshore, as well as intercepting the longshore drift of sand from the north (Spătaru, 1990; Panin et al., 1979-1994). During the second half of the 19th century, channels were cut to shorten the navigation route on Sulina distributary. When this was done, the southern arm of Sfântu Gheorghe lost about 30% of its water discharge and consequently its sediment transport capacity in favour of the shortened arm of Sulina, (Spătaru, 1990). Sulina bed-load accumulates at the end of the jetties as a mouth bar, which is periodically dredged. The dredged sediments are discharged offshore, and thus are lost from the nearshore transport system (Panin et al., 1979-1994). Sulina beach situated just south of the jetties was nourished with sand extracted from Sulina harbour, and two groins were also built.

A revetment was recently built along the southern barrier beaches between Peritesca and Chituc (Postolache et al., 1995). In order to mitigate the beach erosion on these beaches, some Romanian hydrotechnical engineers have proposed to deviate part of the Sfântu Gheorghe distributary water and sediment load farther south, through a channel discharging between Ciotica and Perisor (Hangu et al., 1992). Midia harbour is protected by jetties extending about 5 km offshore; these jetties restrict the amount of sand carried southward by the longshore drift by redirecting it offshore (Fig.1).

Shoreline Dynamics

The northern part of delta coast which includes Chilia delta and Musura Bay beaches, most of it on the Ukrainian territory, has been intensely prograding in the last centuries (Panin, 1985; Mikhailova, 1995). After the Sulina jetties were built at the beginning of the century, the deltaic coast farther was partly isolated from the sediment drift coming from northern Chilia coast. This isolation increased in time with the jetties extension. The jetties can be considered now as impermeable to the sediment drift.

Beach profiles were measured on a network of benchmarks along the delta coast south of Sulina, including one landmark on Sakhalin Island. Based on these, shoreline changes were analysed by Bondar et al., (1983) for the period between 1962 and 1978, and by Vespremeanu and Stefanescu (1988; Fig.4, 5) for the period between 1962 and

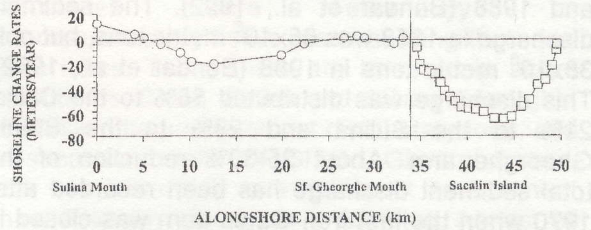

Fig.4 Shoreline change rates (1962 to 1987) from Sulina to Sfântu Gheorghe (from Vespremeanu and Stefănescu, 1978) and for Sacalin Island (1962 to 1993; compiled from Breier and Teodor, 1979 and Panin et al., 1979-1994).

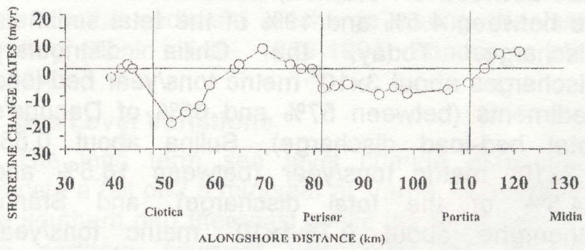

Fig.5 Shoreline change rates between 1962 and 1987 for the deltaic coast situated south of Sacalin Island (data from Vespremeanu and Stefănescu, 1978).

1987. The actual shoreline positions were not published but only the calculated end-point shoreline change rates. Panin et al. (1979-1994) collected annual beach profile measurements after 1978 within the framework of the Romanian Marine Geology and Geoecology institute's "Danube-Black Sea System Monitoring Program". Gâstescu (1979, 1986) published shoreline change analyses for most of the Danube delta coast based on map comparisons.

The shoreline is retreating over almost the entire Danube delta coast situated south of Sulina mouth (Fig.4, 5). The maximum retreat rate for the Sulina-Sfântu Gheorghe sector is over 20 m/yr., which is found at the latitude of Rosulet lake, about 15 km south of Sulina jetties. Almazov et al. (1963) suggested that the highest retreat is due to the divergent of the longshore sediment drift in this zone which may be caused by an anticyclonal eddy attached to the south lee side of the Sulina jetties, generated by a quasipermanent coastal current directed southward. The existence of this divergence zone is also recognised in other sediment drift studies based on radioactive or fluorescent tracers (Dragota, 1973; Bondar and Craciun, 1970), salinity distribution (Bondar, 1964), and physical modelling (Spătaru, 1971). However the divergence zone may be explained by sheltering and diffraction of the waves coming from the Northeast sector. Shoreline recession rates over 10 m/year were also registered along the Sakhalin barrier island, and south of Ciotica and between Portita and Chituc on the southern barrier beaches. The shoreline advances immediately south of Sulina jetties where it is accompanied by intense shoaling of the submerged profile (Bondar and Harabagiu, 1992). The shoreline advances behind Sakhalin island where Sfântu Gheorghe secondary delta is actively prograding, and slowly at Perişor, south of the Ciotica retreating zone, where the shore orientation changes from approximately E-W to a NE-SW direction. Shoreline advance was registered on the southern Chituc spit due the sediment transport obstruction exerted by Midia harbour jetties. The submarine slope also shoals on the sides of Midia structures (Panin et al., 1979-1994).

Nearshore Processes along Sakhalin Barrier

Bratescu (1922), Panin et al. (1979-1994), Breier and Teodor (1979), Vespremeanu (1983), and Bondar et al. (1984) analysed Sakhalin Island genesis and evolution. Sakhalin Island (Fig.1) formed in 1897, from a bar developed south of the Sfântu Gheorghe mouth (Bratescu, 1922). Sediment discharged by Sfântu Gheorghe distributary, and also drifted from north, accumulate as a bar at the mouth of Sfântu Gheorghe. Under the influence of mainly southward sediment drift the mouth bar sands are supposedly transferred south during storms causing a continuing increase in length of Sakhalin island (Panin et al., 1979-1994). At the same time, as observed from successive maps and aerial photos, Sakhalin island shore is retreating, more intensely in its central and southern parts (Panin et al., 1979-1994). The northern half has already been connected to the mainland marshes in 1975 due to both island retreat and Sfântu Gheorghe secondary delta intensive progradation, transforming the island in a spit. Due to its low relief (0.5-1.5 m), the retreat of the island is apparently controlled by overwash and breaching processes as suggested by the numerous successive breaches which appeared over the years following major storms (Panin et al., 1979-1994). The breaches were generally rapidly closed as the wind-induced, and secondarily tidal 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 due to wave refraction pattern typical for this type of areas 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) shows that the island platform built intensively in offshore direction between 1850 and 1923. This process ceased practically afterwards 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 10-12 m depth has flattened while the island retreated. Also bathymetric charts comparisons show that the island platform has been building in the axial (longshore) direction (Jianu and Selariu, 1970). This process extends to a depth of about 12 m and it was uninterrupted though cyclical, between 1858 and 1968 (Bondar et al., 1983). In summary, the island platform building in axial and possibly offshore direction, and also overwash and breaching are the processes that extract sediments from the Sakhalin nearshore system. Using the maps of Breier and Teodor (1979) and Panin et al. (1979-1994; Fig.6), the island shoreline changes for the 1962-1993 period were computed for this study (Fig.4).

Longshore Sediment Transport

There are several direct indicators of the longshore sediment transport direction and magnitude including sand accumulation on opposite sides of engineering structures such as jetties and groins, and the longshore growth of spits and barrier islands, methods which were previously applied on the Danube delta coast. These previous studies indicated that the magnitude of the net longshore transport is

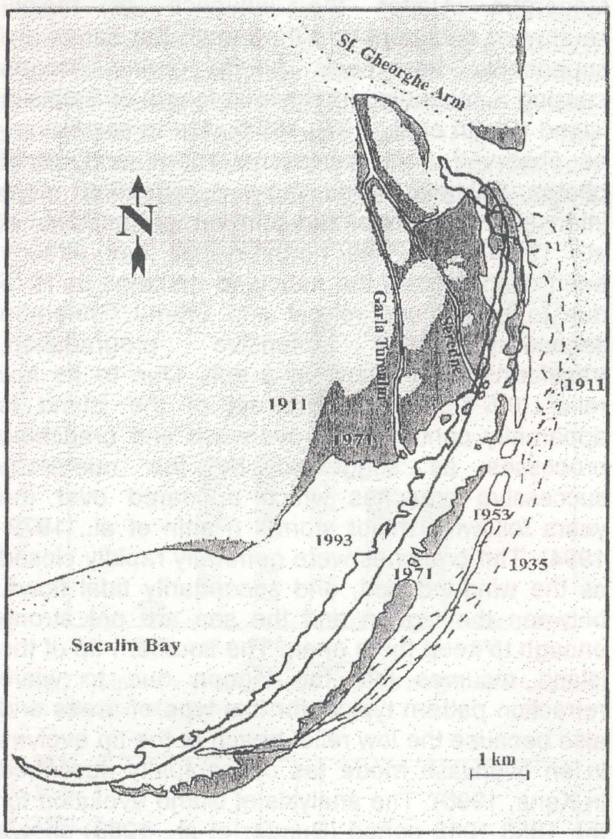

Fig.6 Consecutive positions of Sacalin barrier island (compiled from Breier and Teodor; 1979, Gâstescu, 1979; and Panin et al., 1994).

extremely high. 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. Shuisky (1984) estimated the net sediment transport along Chilia delta to be between 120,000 m^3/year and 850,000 m^3/year, depending on the local orientation of the coast. The southward drift along Chilia can be estimated from the shoaling rates on northern side of Sulina jetties. Bondar and Harabagiu (1992) proposed a value between 1,100,000 and 1,900,000 m^3/year for the shoaling rate but the perimeter for which it was calculated is not clearly specified. The shoaling rate of 500,000 m^3/year to 1,300,000 m^3/year (Bondar and Harabagiu, 1992) on the southern side of the jetties is a direct estimate of the net longshore transport in the reversal zone south of Sulina. The natural shoaling in this area was clearly overestimated since an unknown but substantial amount of sand retrieved from Sulina harbour was discharged on the beach in 1980s. South of the reversal zone to Sfântu Gheorghe, the longshore drift was estimated to 700,000 m^3/year (Panin et al., 1979-1994) from the beach sand deficit. Shuisky (1985) suggested a net longshore sediment transport of 800,000-900,000 m^3/year along the same sector. The Sakhalin barrier island platform building in the axial direction is also a direct indicator of the net longshore transport rate. By using previously estimated shoaling rates to 9 m depth (Bondar et al., 1983), the transport is directed southward at a rate of about 1,080,000 m^3/year. Farther south along Chituc spit, Bondar et al. (1980) estimated the longshore transport by using synoptic wind data. The drift was directed southward at a rate of about 900,000-1,110,000 m^3/year down to the 9 m isobath.

METHODS

Sediment Budget

A sand budget was used to estimate of the longshore sediment transport pattern. 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. The above assumptions, however, would not be valid along barrier beach of Sakhalin the island, since the cross-shore sedimentation by overwash and breaching (Panin et al., 1979-1994), and possibly offshore loss (Bondar et al., 1984; Jianu and Selariu, 1970) are likely to be important. The calculations therefore were not done for Sakhalin island but special consideration was given to the budget here.

The remaining study area was divided into two coastal cells based on the changes of the longshore transport direction and on Danube distributaries sediment discharge. The northern cell was taken between Sulina mouth and Sfântu Gheorghe mouth. The Sulina mouth jetties were considered to be impermeable to sediment transport because they extend almost to the estimated depth of closure. Thus the northern lateral boundary for this cell was considered closed, while the southern one was left open. It is reasonable to assume that the Sfântu Gheorghe distributary sediment discharge is largely directed to the south, in such a way there was no significant contribution from this source to the northern Sulina-Sfântu Gheorghe cell. The southern cell was between Ciotica, situated on the deltaic mainland shore, and Midia. The southern lateral boundary was assumed to be closed because the jetties protecting Midia harbour disrupt the longshore sediment transport by redirecting it offshore. The northern boundary of this cell was left open. Net longshore transport patterns for each cell were derived from the calculated volume changes by integrating them starting at the closed boundaries.

The active beach volume changes were calculated based on shoreline change rates for the period between 1962 and 1987 (Vespremeanu and Stefanescu, 1988; Fig.2 and Fig.3). Because these data do not extend as farther south as Midia harbour, the shoreline progradation rate was considered to be constant southward of the last measurement point and have the same value as measured at that last transect. Although the measurement station used for collecting the shoreline change data were widely spaced along the coast they were considered to represent well the actual shoreline behaviour being very similar to the estimates presented by others (Gâstescu, 1986 and 1993; IUCN, 1992; Spătaru, 1992). The shoreline change rates were corrected for sea level changes by applying Bruun's rule (Inman and Dolan, 1989), assuming a 3 mm/year sea-level rise for the active deltaic shore (i.e. Sulina-Sfântu Gheorghe cell) and a 1.2 mm/year sea-level rise for the Ciotica-Midia cell. An average berm height of 0.5 m was used for the entire coast as the landward boundary. Because suitable submerged beach profile measurement series were unavailable for the Romanian coast, an average depth of closure of 9 m was estimated using Halermeier's method (1981 a, b) based on the available wave data. The annual values for the estimated depth of closure, between 1972 and 1981, ranged between 6 and 12 m. Previous studies of the long-term submerge profile evolution suggest a closure depth between 10 and 12 m (Jianu and Selariu, 1970, Bondar et al., 1984).

Volume changes were calculated using a hybrid model as appropriate, either under assumption that an equilibrium long term beach profile is conserved ("one-line" model; Pelnard-Considere, 1956; Hanson and Kraus, 1989), or that the beach profile general shape is non-conservative during shoreline retreat. During delta formation phase, both the shoreline and the subaqueous delta advance at the same rate, while in the reduction process, the delta shoreline is retreating more rapidly than the subaqueous delta (Refaat and Tsuchiya, 1991). This latter behaviour 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. Thus an equilibrium beach profile is not conserved during the delta reduction process, since the profile slope becomes more gradual. Jimenez and Sanchez-Arcilla (1993) confirmed the above experimental results in the case of Ebro delta. The "one line" model seems appropriate to describe the beach volume changes on a delta coast in the formation phase only. When a deltaic shoreline is retreating, as is the case of the Danube delta coast under study, it is more appropriate to compute the beach volume changes using a wedge-shaped erosional prism. However the accreting sector of the shoreline south of Sulina jetties seems to conserve an equilibrium during its advance (Gâstescu, 1993). Therefore it was reasonable to use the "one-line" model for this sector, as well as for the other advancing shoreline sectors (Perisor, and Chituc). Longshore net sand transport pattern was derived from volume changes for the depths of closure of 6, 9, and 12 m. The result for the 6 and 12 m depth were used to estimate the magnitude range of the net transport. However, the most plausible estimates were considered to be for the average depth of closure of 9 m, and they will be used in further discussions.

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 interval over a 10-year period between 1972 and 1981 were used in the current study (Fig.2, 3). The measurements involved visual observations of a buoy fixed at a water depth of 11 m. The measured characteristics include mean wave height, period, and direction three times daily during the daylight. The wave direction is estimated visually, with an accuracy of about 20^0. Gaps in the record due to periods of poor visibility were filled with statistically significant values (Kraus and Harikai, 1983). Wave data were sparse for other sectors of the coast. Because the wind regime does not vary significantly along the relatively short coast, the wave climate at Constantza was assumed to represent that alone for the entire coast.

The bathymetry was obtained by digitising 1:50,000 scale maps published by the Romanian Navy Hydrographic Service, based on their 1979 survey. Then the observed waves were backward refracted on the real bathymetry around the point were they were measured using iteratively a wave transformation program provided by U.S. Army Corps of Engineers (RCPWAVE; Cialone et al., 1992), 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 figures, the transformed data were not significantly different.

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; Inman and Dolan, 1989). The constant k, which describes the efficiency of longshore component of wave energy flux in transporting sediments, was considered an adjustable parameter. A value of k=0.256, calibrated using the sand budget computations to a depth of 9 m, was used. Both NSTRAN and RCPWAVE are component programs of the "Shoreline Modelling System" (SMS) standardised software collection created by the U.S.Army Corps of Engineers (Hanson and Kraus, 1989). The 140 km-long area extending from Sulina to Midia was divided in six sectors according to the shoreline mean orientation (Fig.7) and the potential net sediment transport was computed for each of them. The resulting patterns were compared to the transport rates computed from the sand budget.

RESULTS

The general pattern of the net longshore transport provided by the sediment budget compared favourably to that calculated by wave energy flux method (Fig.8, 9). The net longshore sediment transport along the entire studied coast is high on average, mainly as a result of both the prevailing E-NE waves superimposed on NNE-SSE general orientation of the coast.

Sulina-Sfântu Gheorghe

From Sulina to Sfântu Gheorghe, the resulting net sediment transport scheme was basically made up of two cells (Fig.8, 10): a sector of northward directed transport situated immediately south of the Sulina jetties with an average rate of 190,000 m^3/year (ranging between 130,000 m^3/year at 6 m depth, and 250,000 m^3/year at 12 m depth) and a longer sector of southward transport farther south to Sfântu Gheorghe which had an average rate of 620,000 m^3/year (with a range between 415,000 m^3/year and 830,000 m^3/year). The magnitude of the transport in the northern cell does not explain the shoaling rate of at least 500,000 m^3/year south of Sulina jetties (Bondar et al., 1992). Presumably the artificial nourishment of the beach with an unknown quantity of sand, is the main factor affecting the budget there. The potential transport calculation also showed a two-cell pattern, but for the northern cell both the length and the net transport were less than those obtained from the sand budget. The two-cell pattern is the result of the sheltering of waves coming from the NE quadrant, and diffraction around the jetties. The poor quality of wave data, poor performance of the wave refraction model adjacent to jetties, the corrupted sand budget, and probably the existence of an attached anticyclonic eddy in this shadow zone (Almazov et al., 1963), all concur in creating the difference between patterns. Other investigators have found that closed attached eddies may from in the lee of capes, jetties, or other topographic indentations of the coast, with consequent modifications to local distributions of sediment deposition (Ferentinos and Collins, 1980; Davies et al., 1995). In the southern cell, the net transport increased from zero at the nodal point, up to 800,000 m^3/year at Câsla Vădanei, remaining fairly constant up to the cell end, at Sfântu Gheorghe (Fig.8). The sediment transport rate north of Câsla Vădanei is lower relative to the rate of transport farther south because of an increase in the submerged beach slope (Fig.7) and the sheltering effect of Sulina jetties.

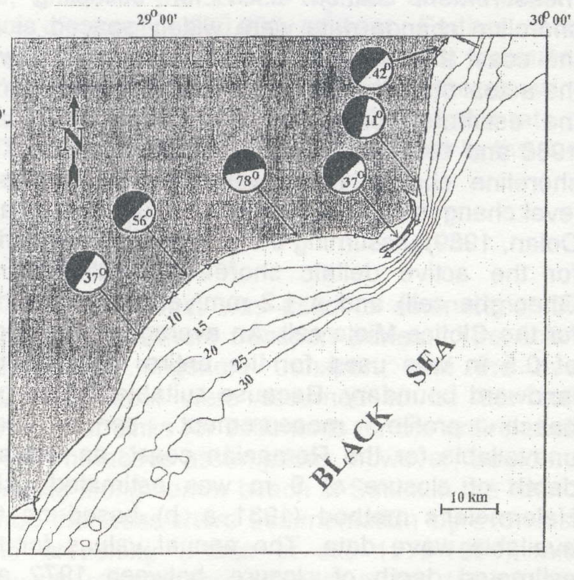

Fig.7 Bathymetry of the study area, and the average orientation of different coast sectors used in computing the potential longshore sediment transport.

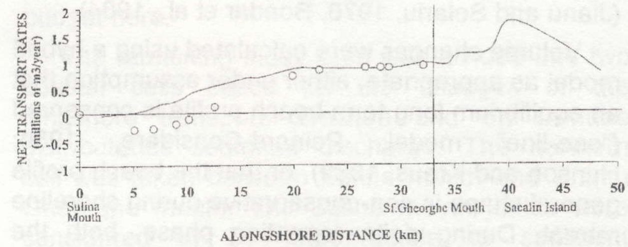

Fig.8 Patterns of net longshore transport (circles) and potential transport (line) between Sulina and the southern tip of Sacalin Island.

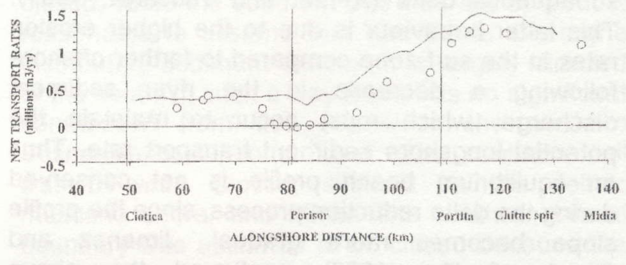

Fig.9 Patterns of net longshore sediment transport for the deltaic coast south of Sacalin barrier island (using same conventions as in fig.8).

Sakhalin Island

Sakhalin island shoreline situated south of Sfântu Gheorghe mouth receded everywhere between 1962 and 1993, reaching the highest retreat rate on the Danube delta coast (66 m/yr.) at the island centre (Fig.4). Consequently the island convexity had been reduced (Fig.6). During this period not only did the island migrate landward but its length also increased with about 1.5 km at the northern tip and 5.5 km at the southern end. It was not possible to compute a sediment budget for the Sakhalin island because measurements of submerged beach profile were not available. However, the pattern of potential longshore transport was estimated using the same value for k (i.e.0.256) as for the entire study area. The net transport directed to the south with an average magnitude of about 1,230,000 m^3/year, and a range between 820,000 m^3/year and 1,640,000 m^3/year. This value was, not unexpectedly, the highest figure on the entire Danube delta coast (Fig.10). Sakhalin average shoreline orientation increases the wave angle of attack, and the steep nearshore gradient minimises wave refraction. The transport increased from about 900,000 m^3/year south of the Sfântu Gheorghe mouth to about 1,750,000 m^3/year in the island median section (Fig.8). For the southern half of the island, the transport showed a decrease to 750,000 m^3/year. This indicates that the southern half of the island should have been accreting but the shoreline retreated instead (Fig.4). Therefore, the shoreline variation must have been controlled by mechanisms other than the longshore sediment transport. Cross-shore sediment transfer processes such as overwash, breaching (Panin et al., 1994), and offshore sediment transport (Bondar et al., 1983 and Bondar et al., 1984) during storms could be more likely to have been responsible for the overall recession of the coast in the southern part of the Sakhalin Island. The northern half of the island was wider and had a field of relatively high foredunes (Panin et al., 1979-1994), which would inhibit cross-island sand transport. The southern half of the island was narrower with a lower relief and more likely to be overtopped and breached during storms.

There is a convergence in net potential transport of about 500,000 m^3/year of sand between the southern tip of the Sakhalin island (Fig.8) and Ciotica on the mainland (Fig.9). This amount of sand was apparently not transported farther south along the coast but accumulated on the axial zone of island platform. Bondar et al. (1983b) estimated this shoaling rate, to a depth of 9 m, at 1,400,000 m^3/year, but for the period between 1858 and 1968. It is also possible that part of the sand entered the bay behind Sakhalin island. The bay behind Sakhalin is known to be shoaling due to Sfântu Gheorghe secondary delta progradation (Panin et al., 1979-1994; Gâstescu, 1979 and 1986; Vespremeanu, 1983), but because no quantitative studies were done in the area, there are no estimates for the sediment flux possibly coming from the offshore.

Ciotica-Midia

The net transport continued to be mainly southward in the Ciotica-Midia sector of the Romanian coast (Fig.9, 10). The general pattern of net transport calculated from the sand budget resembled closely the pattern of the potential transport. In particular, the positions for local minima and maxima in the transport rate were the same. It was expected the cross-shore transport to be significant, where barrier beach separating the Razim-Sinoe lagoon complex from the sea was narrowest, between Portita and Periboina (Fig.1), and therefore to alter the accuracy of the sand budget. Estimates of the overwash processes in this area would increase the accuracy of the model. However, it is expected that the importance of overwash will diminish as a result of the recently built revetment.

A notable discrepancy is a 10 km-long reversal of the transport, along Periteasca beach (Fig.9), which was not found in calculation of the potential sediment transport. The magnitude of the reverse transport, however, was relatively small (8,000 m^3/year on average using the average 9 m depth of closure; taken as negligible, i.e. ~0 in Fig.10). It may have been merely due to uncertainties in the transport magnitudes calculated from the sand budget. Therefore the reversal zone at Perisor as resulted from sediment budget should be considered with caution until new data will improve the accuracy of the budget.

Between Ciotica and Perisor, the net potential transport was directed southward at an average rate of about 270,000 m^3/year (180,000 m^3/year to 6 m depth, and 360,000 m^3/year to 12 m depth; Fig.10). The average rate of the net transport south of the reversal zone to Midia was about 660,000 m^3/year to the south (440,000 m^3/year and 880,000 m^3/year to 6 and 12 m depth respectively; Fig.10). The rate increased from 0 to a maximum of 1,075,000 m^3/year on the northern Chituc spit and decreased afterwards to 775,000 m^3/year at Midia (Fig.9).

The potential transport rate was southward for the entire Ciotica-Midia stretch. A decrease in the rate between km.78 and km.85 indicated that the shoreline in Perisor sector was advancing (Fig.9), but it underestimated both the intensity of accretion, and the alongshore extension of the accretionary zone. Further calibration based on a more accurate sand budget would be needed to clarify the discrepancies.

DISCUSSION

Chilia lobe is the only part of Danube delta intensely prograding. Sfântu Gheorghe distributary is in equilibrium on its northern side, progradation being active in the secondary delta behind Sakhalin island. The earlier lobe of Sulina continues to be reworked in an accelerated regime under anthropogenic influence (i.e. dredging, jettied mouth). Furthermore the entire coast south

Fig.10 Longshore sediment transport model for the Danube Delta coast (the transport along Chilia lobe is from Shuisky, 1984). Transport rates in thousands of cubic meters per year. Circled + and – represent advancing and retreating sectors respectively.

of Sulina is isolated form Chilia lobe by Sulina jetties. The coast between Sulina and Midia has retreated at very high rates in the last decades, under very energetic waves due to their acute angle of attack, and poor refraction on relatively steep nearshore. Since this part of the coast is closed laterally to north and south by impermeable structures, shoreline changes were due to the longshore transport that redistributed sand from an area to another. Cross-shore landward sediment transfer processes appear to be important for the Sakhalin barrier island, and potentially for the narrow sandy barrier beach between Peritesca and Chituc. Sediment transfer to the offshore is probably active on the steep Sakhalin beach, and is also induced by the jetties at Midia.

About 800,000 m^3/year of sand are lost for the nearshore system by maintenance dredging of Sulina mouth. This amount would be enough to keep the shoreline south in equilibrium. If bypassed south of the reversal zone adjacent to the jetties, it will possibly stop shoreline retreat. The sediment transport reversal is responsible for trapping sand in the side of the Sulina jetties, increasing downstream beach starvation.

Sfântu Gheorghe distributary also discharged about 800,000 m^3/year of sand. The potential sediment transport indicates that the average rate of beach retreat on northern Sakhalin, which was about 35 m/year, would more than double if this sediment input would disappear. The sand passing the southern tip of Sakhalin island contributes to the island platform building, and it is not able to feed the beaches farther south since the shoreline orientation changes abruptly. Continued retreat of the island will enhance bypassing of sediments to the south.

The change in coast orientation south at Periteasca, under the present wave climate, favours longshore transport convergence, and thus beach accretion. This sector acts as a buffer for the sand transport farther south, increasing even more sand starvation of beaches. The proposed channel to deviate some of the Sfântu Gheorghe distributary discharge farther south, between Ciotica and Perisor, as a solution to reduce the erosion, would probably reduce the shoreline locally in a zone of relatively reduced economic and ecological importance, but the Sakhalin beach will have to compensate the loss via erosion. The island beach, already has the highest shoreline retreat rate on the Romanian coast, would became additionally sand-starved by applying this plan, endangering the rich Sakhalin bay wildlife habitat. Furthermore, the solution does not seem viable for stabilising beaches south of the buffer zone.

The area with highest potential risk is the narrow barrier between Periteasca and Periboina, even though the sand accumulation zone upstream the Midia jetties may eventually provide some positive effects on a longer time scale. On the other hand, the sand trapped upstream Midia harbour starves of sand the southern Romanian coast where most of public beaches and tourist objectives were developed. It can be anticipated that the time when the trapped sand will be artificially bypassed south of Midia is not too far away since other protection solution applied Mamaia beach were not particularly successful. Alternately, the development pressure may relocate to the northern beaches on the Danube delta coast.

CONCLUSIONS and RECOMMENDATIONS

The long-term recessional character of the beach between Sulina and Midia is prescribed by the alternate channel switching process, characteristic for Danube delta evolution. As a consequence in the last centuries, Danube discharged mostly through the northern distributary of Chilia. The shoreline of previously built lobe of Sulina retreats, as it is being reworked under the longshore sand transport induced by the high energetic level and acute angle of wave attack. Sfântu Gheorghe lobe has ceased to prograde, except for the sheltered area behind Sakhalin island. The shoreline evolution was negatively influenced by the engineering works at Sulina mouth and Midia harbour, and most probably, by the natural and human induced decrease of the Danube sediment discharge. The negative effect of damming on the Danube sediment load was attenuated by erosion of the river bottom and islets in the lower course and by artificial meander cut-offs in the delta. Because the sand deficit is potentially high, the restoration of the entire coast between Sulina and Midia may be financially prohibitive, and a system of priorities must be established. An array of restoration strategies with minimum negative effect for adjacent beaches, including beach nourishment, sand bypassing, and detached breakwaters, are needed.

Increased coverage and accuracy of wave measurements would probably provide the greatest improvement in future studies. Three new gauges are planned to be installed along the coast. At least one of them should be situated between Ciotica and Periteasca where shoreline orientation changes abruptly. For the highly active Danube delta coast, monitoring would include aerial coverage of the area at least once a year; beach profiling to the depth of closure on an more closely spaced landmark network, 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 Sulina and Sfântu Gheorghe mouths, and Sakhalin 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 not to be dependent on their sediment discharge.

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