

**Hydrology
and morphology of two
river mouth regions
(temperate Vistula Delta
and subtropical Red River
Delta)**

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Abstract

The paper presents a comparative analysis of two different river mouths from two different geographical zones (subtropical and temperate climatic regions). One is the multi-branch and multi-spit mouth of the Red River on the Gulf of Tonkin (Vietnam), the other is the smaller delta of the river Vistula on a bay of the Baltic Sea (Poland). The analysis focuses on the similarities and differences in the hydrodynamics between these estuaries and the adjacent coastal zones, the features of sediment transport, and the long-term morphodynamics of the river outlets. Salinity and water level are also discussed, the latter also in the context of the anticipated global effect of accelerated sea level rise. The analysis shows

The complete text of the paper is available at <http://www.iopan.gda.pl/oceanologia/>

that the climatic and environmental conditions associated with geographical zones give rise to fundamental differences in the generation and dynamic evolution of the river mouths.

1. Introduction

All over the world, coastal regions, particularly those around river mouths, are urbanised to a substantial extent and inhabited by relatively large human populations. At most river mouths, sea-river interactions result in vast accumulative forms in front of the mouth, such as fan-deltas, shoals, small islands or low-lying areas of land with complex systems of channels. Most often, these forms are made up of river sediments discharged into the coastal zone. In some circumstances, however, erosion of the stable delta of a large river can be initiated by human activities carried out upstream, for example, the construction of a dam. This kind of situation has arisen in the Nile Delta, where accumulative processes have ceased as a result of the deficit of river sediment and erosion has begun (see Stanley 1996). Generally speaking, river deltas are a vast and very complex subject that has been studied by many researchers for a long time: see e.g. Wright & Coleman (1972, 1973), Coleman & Wright (1973), Galloway (1975), Wright (1977, 1985), Nemeč & Steel (1988), Hoekstra (1989), Orton & Reading (1993).

River mouths are distinguished by specific features and phenomena, which give rise to significant differences between them. The most important of these features are:

- considerable and rapid change of water level at river mouths due to sea-borne effects. These may be represented by a regular tidal wave of the bore type, similar – though on a much smaller scale – to a tsunami wave (see Pan et al. (2003));
- temporary (seasonal) freezing of water at river mouths causing ice jams, which can affect the hydrodynamics of the outlet, e.g. the Vistula flowing into the Baltic Sea;
- the offshore transport of vast amounts of fine sediment in conjunction with seasonal monsoons. Such processes are typical of large river deltas located in subtropical regions, e.g. the Red River and Mekong deltas in Vietnam;
- the level of human pressure and technical intervention in the natural river environment (see Orton & Reading (1993), Stanley (1996)).

The diversity of river mouths is reflected in the numerous possible criteria for classifying them. Geographical location is one such criterion that defines the characteristic hydrological conditions with considerable accuracy. On this basis, existing river mouths have been split into two

groups. One of these groups comprises large rivers located in lower latitudes, where phenomena typical of subtropical climates occur. As a general rule, the flora and fauna there supply vast amounts of organic matter and predominantly a fine cohesive sediment, which is dispersed far offshore with varying intensity depending on the monsoon seasons. The mouth of such a river is usually characterised by a more dynamic bathymetric layout, covering a greater area, with numerous shoals and channels. The shoals are subject to an on-going evolution that is more rapid in comparison with river mouths at higher latitudes; they are also continually spreading seawards. Characteristic of the mouths of the larger rivers, such shoals are strongly influenced by several processes: large, river-borne sediment transport; intensive coastal wave-current motion and river flow; and strong tidal flows causing movement of sediment some distance from the mouth. The other group includes rivers located at higher latitudes, in regions where temperatures are lower and biological life is poorer, which implies smaller amounts of organic matter. The system of shoals close by the mouth of such a river is relatively compact, consisting at most of a few channels which spread gradually in an offshore direction. Here it is river-borne sediments (mainly sand) that play the dominant role, but periodic ice-related phenomena can also play a not insignificant part. With this classification of river mouths in mind, we can go on to distinguish a third, intermediate group of estuaries and deltas. In this case, the values of the characteristic parameters, that is, latitude, sediment transport rates for fine and coarse material, hydrodynamic features, etc. are transitional. The Yellow River delta is an example of one such river (Li & Wang 2003).

The present work compares and analyses two different river mouths, one from each of the two main groups specified above. One is the multi-branch and multi-spit mouth of the Red River on the Gulf of Tonkin (Vietnam), the other is the smaller delta of the river Vistula (Wisła) on a bay of the Baltic Sea (Poland). The former is formed by factors and forces typical of subtropical zones, related mostly to summer and winter monsoons, typhoons, strong tidal currents, and the occurrence of heterogeneous fine material containing numerous organic admixtures. The latter is evolving as a result of extreme river discharges during spring caused by ice melt (accompanied by ice jams at the mouth), as well as storm surges, waves and wave-induced currents. Here, the predominantly sandy sediment forming the river mouth is much more uniform and non-cohesive. The study is a comparative analysis of the fundamental hydrodynamic and morphodynamic features of these two river mouth regions and the identification of similarities and differences between these features, if they are present in both cases. In view of recently observed climatic changes, the study also addresses the problem

of flooding at both sites, related to the anticipated acceleration in sea level rise. Together with the natural fresh water and sediment, terrigenous contaminants enter the seas with riverine water, so an understanding of the hydrodynamic and morphological patterns at these river mouths is very important as regards protecting the coastal environment and the integrated management of coastal zones.

2. Site description

2.1. The non-tidal river mouth (site I)

With a catchment area of 194 000 km², the river Vistula and its mouth constitute the most extensive hydrological system connected to the non-tidal Baltic Sea. The Vistula delta plain (Żuławy) covers an area of 2320 km² and has an average human population density of 145 inhabitants per km². The medium-scale Vistula delta is closely associated with the coastal shoals typically forming at river mouths in non-tidal or micro-tidal regions. In the 19th century, catastrophic floods in the Vistula delta led to the decision to construct a new direct river outlet in 1895 and to sever the other branches from the main river channel (see Fig. 1). Since then an accumulative form known as a fan-delta has been accumulating in the nearshore zone, in front of the river mouth.

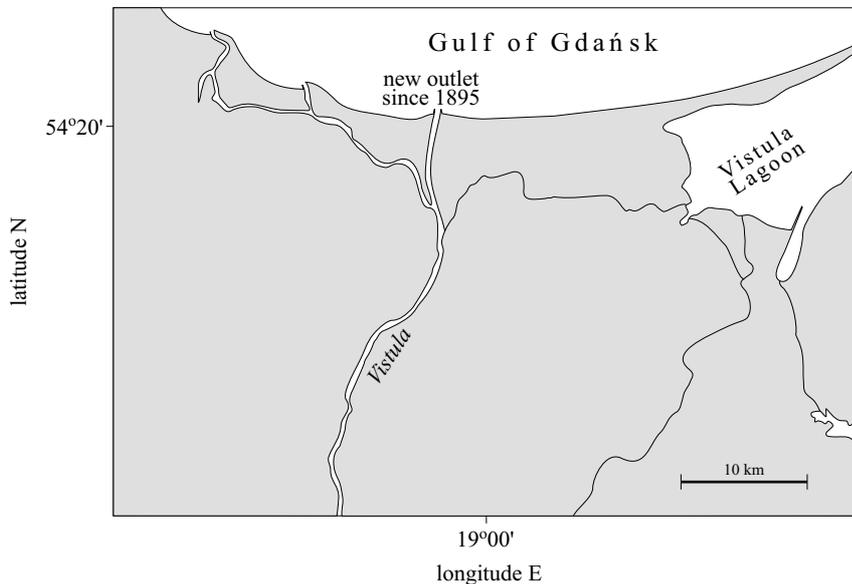


Fig. 1. General layout of the Vistula delta with the old inactive branches and the present active outlet

The changes in the main Vistula mouth are associated with the estuarine sedimentation of sand carried by the river. The maintenance of the outlet requires groynes, which have to be lengthened continually. Regulation of the river mouth with the use of groynes was assumed to be the only efficient way of concentrating the river current at the land-sea transition point, thus taking advantage of the river's natural capacity to erode a channel in the nearshore shoals. Part of the river-borne sediment is returned to the shore, which results in successive shore accretion. Analysis of archival data shows that the shoreline has advanced by about 2 km since the construction of the new mouth in 1895.

2.2. The tidal river mouth (site II)

The catchment area of the Red River (RR) is about 169 000 km². Before reaching the Ba Lat mouth, the Red River distributes its flow through five branches (see Fig. 2) with 25% of the flow of the Red River discharging into the sea via the Ba Lat mouth. The annual discharge of the RR is about 137×10^9 m³ of water and 116×10^6 tons of suspended sediment. According to this ratio, 34×10^9 m³ of water and 29×10^6 tons of suspended sediment are transported through the Ba Lat mouth every year. At present, the amounts of water and sediment carried by the RR to the sea are decreasing significantly as a result of anthropogenic effects. The coastal lands of Vietnam are densely populated, especially the highly fertile soils of the Red River delta (RRD). 17 million people live on only 16 644 km² of land in the RRD plain and this area accounts for 20% of the rice production in Vietnam. An enormous volume of RR water is needed for irrigation and the demand for water is most pressing in the dry season. Built in 1987 on the Da river, the largest tributary of the RR, the Hoa Binh reservoir covers an area of 208 km² and holds 9.5×10^9 m³ of water. In consequence, the amounts of water and sediment transported through the Ba Lat mouth have fallen significantly, and shipping conditions in the mouth have deteriorated. The other human activities involve deforestation in the upper basin of the RR, which then leads to flooding in its lower reaches. Moreover, reclamation has changed the directions of the main channels in the Ba Lat mouth and caused it to stretch even further out to sea. All these human activities have had a strong influence on the environmental conditions in the RR coastal zone and have increased the risk of flooding, erosion, sedimentation, saltwater intrusion and environmental pollution from various sources.

The hydrodynamics and morphodynamics of the Red River delta, including the estuary of the Ba Lat, have been subjected to thorough field and theoretical investigations, see e.g. Van Maren (2004), Van Maren & Hoekstra (2004).

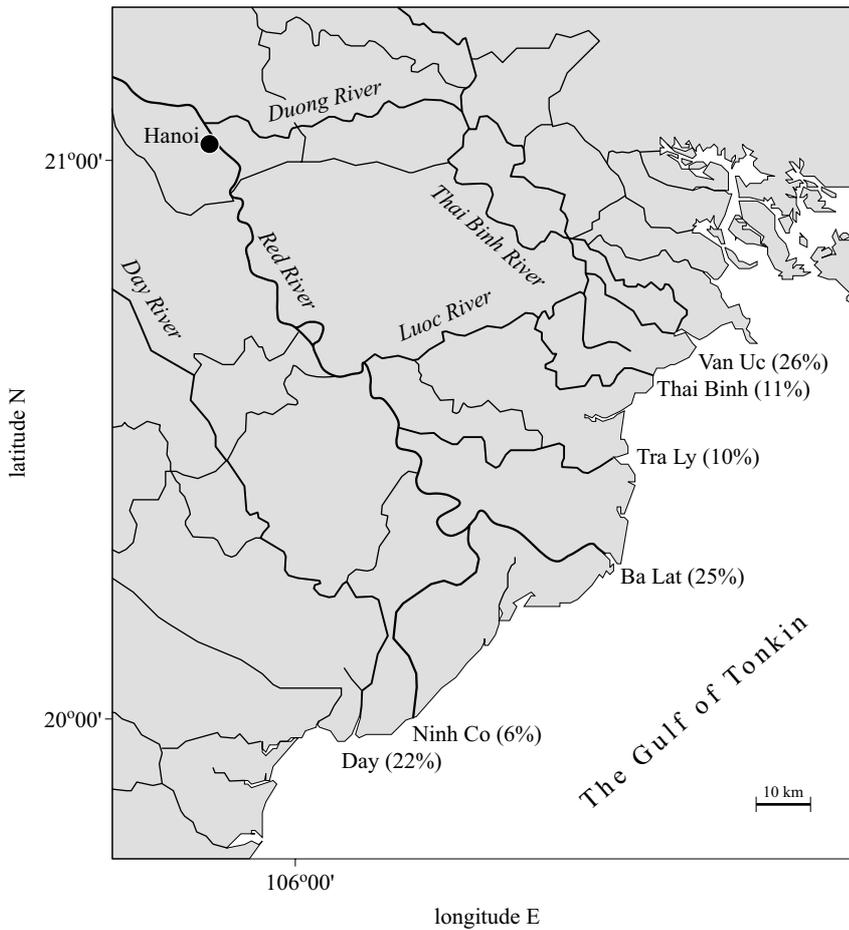


Fig. 2. The Ba Lat mouth and general layout of the Red River delta with the discharge percentage given for each outlet

3. Field data and analysis

Many investigations have been carried out in both of these regions, mostly *in situ*. Among other things, water discharges under various conditions have been surveyed, with the result that the characteristic discharges have been determined, and the probability of their occurrence assigned. Existing data on wind speeds and directions have enabled the formulation of a so-called meteorological mean year and the determination of maximum velocities and durations of wind occurring once in a specified period of time, e.g. once per 100 years. Few sets of data on waves and currents are available for either site. However, the bathymetric data are quite comprehensive for both, even though the river mouth morphologies

are subject to very dynamic change in both time and space. The assessments of sediment transport rates have been obtained by comparative analysis of the bathymetric layouts over time, as well as the use of various theoretical formulas.

3.1. Hydro-meteorological and hydrodynamic conditions

3.1.1. Site I

Hydrology

Hydro-meteorological conditions play an important role in the development of the fan-delta at the Vistula mouth. Available analyses and field surveys reveal that the maximum range of water level set-up does not exceed 50 km upriver during extreme storm conditions. Annual characteristic discharges determined 50 km from the mouth for the period 1951–1990 show that the average rate of flow near the Vistula mouth is $1080 \text{ m}^3 \text{ s}^{-1}$. Maximum and minimum discharges can attain levels of $8000 \text{ m}^3 \text{ s}^{-1}$ and $250 \text{ m}^3 \text{ s}^{-1}$, respectively, and depend mainly on seasonal rainfall and ice/snow melt in the winter and spring.

The experimental investigations, both in the field and using a 3D laboratory model, have yielded flow velocities at the Vistula mouth varying from $V \approx 0.8 \text{ m s}^{-1}$ for a discharge of $Q = 1200\text{--}1500 \text{ m}^3 \text{ s}^{-1}$ to $V \approx 2.4 \text{ m s}^{-1}$ for $Q \approx 5000 \text{ m}^3 \text{ s}^{-1}$. Hence, the mean discharge of approximately $1000 \text{ m}^3 \text{ s}^{-1}$ corresponds to relatively small velocities, which do not give rise to significant depth changes at the fan-delta.

Wind conditions can affect the water flow near the Vistula mouth. Westerly winds (SW, W and NW) prevail for about 41% of the time, while easterlies (NE, E and SE) blow for 23% of the time. Mean wind speeds are c. 4.8 m s^{-1} and 3.7 m s^{-1} for westerlies and easterlies respectively. Storm surges in the sea and backflows are generated mostly by NW and NE winds. During the period 1951–1975 the water level ranged from 416 to 616 cm (the mean sea water level, corresponding to the Amsterdam zero is equal to 500 cm). The influence of the sea level at the mouth is most evident during autumn and winter. The lowest sea water levels, when winds have a southerly component, are recorded mainly in the spring-summer and summer seasons. River discharge can affect the water level at the river mouth very significantly. The highest discharges occur in early spring, as a result of ice and snow melt in the entire catchment area of the Vistula and its tributaries, and in summer (mainly in July) as a result of high rainfall. Analysis of water levels recorded at the stations in the coastal zone near the Vistula mouth has yielded the following:

- the duration of an average storm surge exceeding 550 cm (i.e. 50 cm above mean sea level) is about 30 hours, that of one exceeding 580 cm is about 9 hours;
- the mean low water level lies at 442 cm; the lowest ever level of only 395 cm was recorded in 1887; in the period 1946–1976 the lowest water level was 416 cm;
- in the period 1896–1975, the mean water level was $498.7 \text{ cm} \pm 0.54 \text{ cm}$, while the mean long-term maximum was 585 cm;
- the maximum level corresponding to the probability of $p = 0.1\%$ is 678 cm, the minimum is 387 cm; for $p = 1\%$ the respective values are 647 and 402 cm.

The maximum salinity in the near-bottom water layer at the mouth does not exceed 8.0 PSU, while in the surface layer it is about 1.3 PSU; the mean salinity at the Vistula delta is only 0.3 PSU. The salinity at the mouth is seasonally variable, the maximum being recorded in December, the minimum in April. Backflows of sea water are rather rare and do not penetrate more than a few kilometres upriver. Consisting only of weakly saline coastal waters, they usually occur as a combination of storm surges and low water levels in the Vistula.

Catastrophic flooding caused by ice jams was the main reason for constructing the artificial Vistula outlet in 1895. Even though ice jams occur there almost every year and always result in a significant rise in water level, the region has since that time never been seriously inundated as a result of ice jams at the Vistula mouth. Fortunately, the services responsible for keeping the Vistula mouth clear of ice are extremely vigilant and see to it that potentially dangerous ice jams there are broken up in good time by icebreakers. Minimising the threat of flooding caused by ice jams means determining the mouth's configuration: ice and water will flow freely out to sea if the bathymetric situation is favourable, i.e. there is no blockage by shoals and islands.

Waves, currents and storm surges

Wave measurements and field observations in this respect have been made only sporadically. More information on the wave climate has been obtained theoretically from past meteorological records of atmospheric pressure and wind parameters. Wave climate parameters (height and mean period) were computed for a two-year period (1998–1999) using the well-known and reliable WAM model for a point located about 6.5 km NNW of the tips of the existing Vistula mouth groynes. The computations yielded the following representative wave parameters:

- 1998; significant wave height $H_s = 0.64$ m and mean wave period $T = 3.8$ s,
- 1999; significant wave height $H_s = 0.56$ m and mean wave period $T = 3.6$ s.

The computations indicate that during almost 20% of the mean statistical year, wave motion is predominantly from westerly directions, and during 12.5% of this year from easterly directions. If we also include the 4% duration of waves from the north, we can conclude that for almost 64% of the year, wave motion does not affect the evolution of the Vistula fan-delta. According to the wave data, waves no higher than 1 m are most likely off the river mouth. The annual representative wave parameters are assumed to be $H_s = 0.6$ m and $T = 3.7$ s.

Most often, the uppermost coordinates of the shoals at the fan-delta of the Vistula can locally be higher than the mean sea water level. These shoals are therefore vulnerable to washout, particularly when wave motion is strong and there is a simultaneous storm surge. Apart from flood discharges in the river, these coastal phenomena play a key role in the evolution of the bathymetry at the land-sea interface at site I.

3.1.2. Site II

Hydrology

The Red River is dominated by a monsoon climate, so its hydrological regime is closely connected with the monsoon seasons. The north-east monsoon, occurring in the dry season, lasts from November to May with about 25% of the total annual discharge and with a minimum volume of approximately 2% in March. The flood season during the south-west monsoon lasts 5 months from June to October and carries 75% of the total annual discharge with the peak in August (21%). The average dry season discharge at the Son Tay hydrological station is $1200 \text{ m}^3 \text{ s}^{-1}$ while during the flood season this figure is $14\,000 \text{ m}^3 \text{ s}^{-1}$; the highest ever maximum of $33\,600 \text{ m}^3 \text{ s}^{-1}$ was recorded in August 1971. Based on the ratio of water discharge through the Ba Lat mouth and the total discharge of RR, the average water discharge through the Ba Lat mouth is about $300 \text{ m}^3 \text{ s}^{-1}$ and $3500 \text{ m}^3 \text{ s}^{-1}$ during the dry and flood seasons respectively. The situation where high water levels during the flood season coincide with spring tides and storm surges is of the utmost importance for the people inhabiting the lower RRD plain. The lower RRD basin can be divided into different areas with various hydrological regimes: the area not affected by tides, the area slightly affected by tides, the area governed both by flood and tides, and the area essentially controlled by the tidal regime. In fact, the whole of the

Ba Lat estuary lies within these last two areas. One of the main hydrological characteristics of the river mouth is the behaviour of the river water during the dry and flood seasons. From current data measured at a station in the entrance of the Ba Lat mouth during the flood and dry seasons of 2000, it appears that the outflow lasts longer than the inflow, especially during the flood season (outflow – 19 h, inflow – 6 h; respective maximum velocities 1.2 m s^{-1} and 0.4 m s^{-1}).

The interface between saline and fresh water depends on the river flow, the tidal cycle and the river morphology. During the dry season, especially in February, March and April, saline intrusions into the Red River via the Ba Lat mouth are significant. The isohaline of 1 PSU during this season may lie some 21 km upstream in the flood cycle of the spring tide. The situation is reversed during the flood season, when fresh water often spreads a long way out to sea, as far as 10 km off the Ba Lat mouth.

Wave, current and sea level variations

Along the RRD coastline, waves, currents and sea level variations are defined mainly by the monsoon and typhoon regime. The offshore wave climate has been determined on the basis of a 20-year series of wind speed and direction measurements at the Bach Long Vi ($20^{\circ}08'N$, $107^{\circ}43'E$) station (6 hour interval), which lies about 100 km east of the Ba Lat mouth. The results show that the wave regime in the Gulf of Tonkin is defined primarily by the monsoon wind climate. Thus, there are two prevailing wave directions – NE and S – associated with the winter and summer monsoons respectively. Table 1 summarises the significant wave height and period, depending on direction and the total number of wave events, as an annual average in 17 m of water off the Ba Lat mouth.

Table 1. Annual average significant wave height H_s and period T , and total number of events n , depending on direction, off the Ba Lat mouth (time period: 1976–1995)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	Calm
H_s [m]	1.22	1.60	2.05	1.47	1.35	1.15	1.54	1.99	1.73	–
T [s]	5.0	6.0	7.0	6.0	6.0	6.0	6.0	8.0	7.0	–
n	1604	3211	7962	1466	3054	972	1850	1415	4922	2028

Just off the Ba Lat mouth, there are some distinct coastal current systems forming a complicated nearshore circulation pattern. The most dominant currents are tidal, wind-driven, wave-driven, and river currents. During the dry season, the observed maximum outflow velocities (river flow

plus ebb-tide flow) were systematically higher than the inflow velocities: 0.45 m s^{-1} during spring tides and 0.25 m s^{-1} during neap tides for the outflow phase, and 0.25 m s^{-1} during spring tides and 0.0 during neap tides for the inflow phase, respectively. During the flood season, strong outflows of fresh water predominate in all the current phases. The maximum outflow velocity can reach 1.2 m s^{-1} (during the flood season of 2000), and the outflow is permanent during both neap and spring tides. The open area off the Ba Lat mouth is subject to the influence of the wind-driven current. Because of the seasonal change in wind direction and the nearshore topography, the monthly average wind-driven current was found to be about 0.1 to 0.3 m s^{-1} south-westwards during winter and north-eastwards during summer. The prevailing direction of the net annual littoral current at the Ba Lat mouth is south-westerly owing to the dominant direction of the winter monsoon.

According to the zoning of the tidal parameters in the seas around Vietnam in general and in the Gulf of Tonkin in particular, the tide at the Ba Lat mouth is diurnal with an amplitude varying from 1.9 to 2.6 m . The average tidal amplitude in the period from 1972 to 1990 was 1.92 m , with the maximum tidal level amplitude of 3.64 m being recorded on December 23, 1987. In this region, special attention is paid to irregular sea-water level changes during monsoons and typhoons. The high irregular water levels in the estuary are extremely dangerous when typhoon or monsoon surges coincide with a spring tide. They often result in damage to infrastructure, sea and river dyke systems, or at the very least give rise to saline intrusions in the winter season, when the coincidence of winter monsoon surges and spring tides is likely. The distribution of storm surges along the western coast of the Gulf of Tonkin has been obtained on the basis of data relating to 104 tropical storms in the region from 16° to 24°N (The East Sea Monograph 2003) (see Table 2).

Table 2. Typhoon surge distribution [%] along the Western coastline of the Gulf of Tonkin

Parts of the coastline (latitude N)	Typhoon surge magnitudes [cm]					
	≤ 20	20–50	5–100	100–150	150–200	≥ 200
from 22° to 21°	58	38	5	6	2	
from 21° to 20°	35	38	17	8	3	
from 20° to 19°	41	34	15	9	1	1
from 19° to 18°	46	37	10	5	2	1
from 18° to 17°	71	18	8	2	1	
from 17° to 16°	95	4	1			1

The Ba Lat mouth is located in the second latitudinal range (from 21° to 20°, see Fig. 2), which is regarded as one of the most dangerous areas for typhoon surges. The maximum monsoon surge is approximately 0.4 m for the region in question.

3.2. Morphodynamics

3.2.1. Site I

Since the construction of the artificial Vistula outlet in 1895, the river mouth has evolved as a result of on-going sedimentation in front of it. In the beginning, this process was very intensive. At present, estuarine sedimentation is observed only directly off the Vistula mouth, and takes the form of a highly convoluted fan-delta, with shoals, small islands, and deep underwater channels. There may be from 1 to 3 of these and their location is variable. In winter the fan-delta creates conditions favourable for the formation of ice jams, which constitute a serious navigational obstacle for fishing boats and icebreakers. It is worth pointing out that part of the accumulated sand is washed away by waves and wave-induced currents. The volumetric balance, however, is definitely positive, which means that much more sediment is supplied and accumulated by the river than is eroded by marine processes.

Every year, the Vistula carries 0.6–1.5 million m³ of sediment to the sea. On the other hand, about 130 000 m³ of sandy material is eroded from the fan-delta during the same period as a result of the action of waves and currents. In 1958 the volume of the delta as far down as the 15 m isobath was c. 100 million m³ and the annual volumetric accretion was said to be continually decreasing. According to other assessments for the period 1970–1995, the accretion rate lies in the 0.3–0.45 million m³ per year range. Sieve analyses of sand sampled at the fan-delta have shown that the coarsest sediment ($d_{50} = 0.55\text{--}1.0$ mm) occurs in the delta channels and in the midstream at the mouth, while the plateau of the fan-delta is made up of medium-grained sand ($d_{50} = 0.25\text{--}1.0$ mm). The sea bed of the coastal zone beyond the delta consists of fine and medium sediment.

Analysis of the available bathymetric records, covering the period 1894–2003, in a unified geodesic system ensured that calculations of accretion in the delta were precise. All the calculations were carried out in the same grid, with the 1894 bathymetry as the initial situation. Fig. 3 shows the volumes of the fan-delta calculated for consecutive years. It can be seen from this figure that the delta volume has been increasing gradually all the time. The approximation yields an annual accretion of 1.3 million m³. The longshore sediment transport rates estimated for the eastern and western sides of the delta suggest an annual erosion of more than 100 000 m³. Summing the

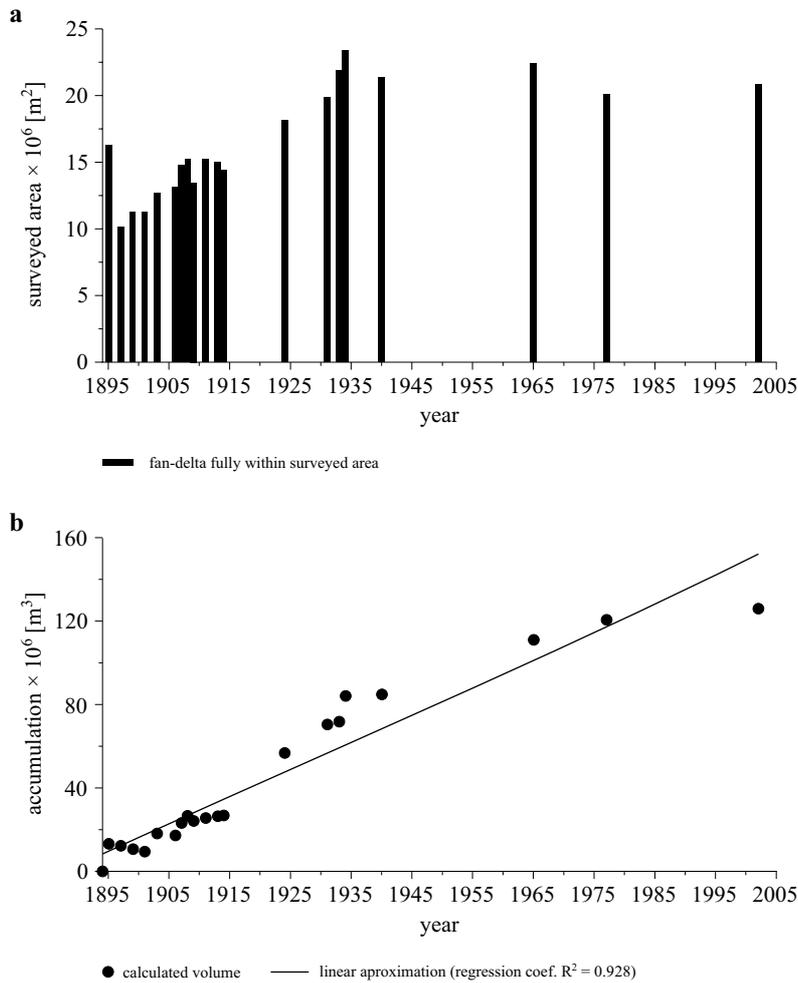


Fig. 3. Areas subject to bathymetric surveys (a) and the calculated cumulative volume of sediment in the coastal zone (b) at the Vistula mouth from 1895 to 2002 (by courtesy of BMT Cordah Ltd., Gdańsk)

above two quantities yields an average annual total of c. 1.4 million m³ of sand transported by the Vistula to the sea. This conclusion is coincident with the upper limit of the rough estimates (1.5 million m³ per year). By 2003 a total of about 126 million m³ of sediment had been deposited in the fan-delta.

3.2.2. Site II

There is a remarkable trend in the variation of the dominant roles of tide and waves in the northern and southern parts of the Red River mouths.

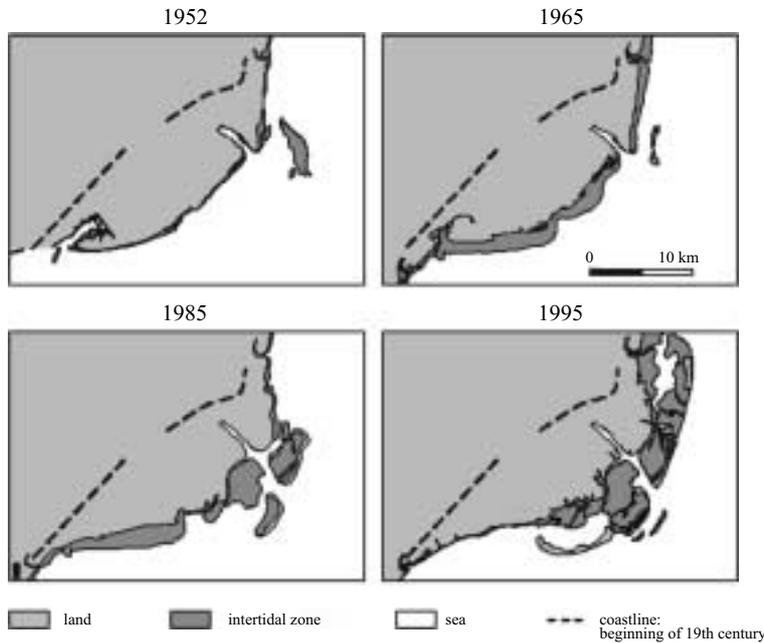


Fig. 4. The evolution of the Ba Lat delta from 1952 to 1995 (the dashed line represents the coastline at the beginning of the 19th century)

While the river mouths in the north are often tunnel-shaped, because of the prevalence of river and tidal forces, the river mouths in the south are often convex in shape, which is the upshot of the dominant wave forces. The shape of the Ba Lat mouth is thus due to a mixture of wave and tidal impacts.

Every year about 29 millions tons of suspended sediment are transported through the Ba Lat mouth. This gigantic volume of sediment is the source from which the Ba Lat delta is formed. Having settled at the bottom, these sediments are then redistributed by waves, tides and currents, which are very closely linked to the seasonal climate. During the dry season, the degree of mixing is higher in comparison with the wet season owing to the longer period of intensive mixing related to the ebb-flood tidal cycle. During the flood season, the longitudinal density gradient causes the stratification to increase. This is sufficiently strong to generate a gravitational circulation in the Ba Lat estuary. But landward sediment transport is prevented by the enormous volume of fresh water discharging to the sea during the flood season. In the dry season, the discharging sediment accumulates mainly along the shoreline, whereas the river flow in the flood season spreads very far out to sea. Consequently, the motion of the sediment tends to be directed offshore. Owing to the significant amount of cohesive material, flocculation

of suspended sediment is expected to occur at the end of the ebb period: this often happens with the sediment entering the mangrove swamps surrounding the Ba Lat estuary.

The Ba Lat mouth is flanked by an extensive bi-directional spit system. During the flood season (summer), waves come predominantly from the south and south-east, and wave-induced currents transport sediment to the north, forming a spit pointing northwards. The reverse situation occurs during the dry season with north-easterly waves, which give rise to a south-pointing spit. In general, the Ba Lat delta is extending offshore at a rate of 30–50 m per year. Fig. 4 shows the evolution of the Ba Lat mouth and delta for four periods from 1952 to 1995.

4. The impact of sea level rise on the Vistula Delta and the Red River Delta

The phenomenon of sea level rise (SLR) is not new and a natural rate of SLR of about 0.1 to 0.2 m per 100 years is being experienced at present. Owing to accumulated man-made greenhouse gases in the atmosphere and the depletion of the ozone layer, climate change effects are expected to take place that will cause global warming and an accelerated rate of SLR over the coming century. According to the latest predictions, the rate of SLR will accelerate to between 0.3 m and 1 m per 100 years.

4.1. The Vistula Delta

A substantial part of the Vistula delta plain lies almost 2 m below the present sea level. This makes this region susceptible to potentially serious flooding as SLR progresses. The long-term annual sea-level rise (recorded from 1883 to 1985) in the Vistula estuary region was 1.5–2.0 mm per year. This means that during the last century the mean rate of SLR was approximately about 0.15–0.20 m per 100 years. In recent decades, the rate of SLR has accelerated considerably. It appears from recent analyses and predictions that the present trend in accelerated sea level rise (ASLR) will cause a rise of 0.2 m by 2050 and 0.5 m by 2100 (Pruszek & Zawadzka, in press). The more frequent occurrence of extreme phenomena, such as severe storms, are additional threats resulting from climate change. Since 1970 the frequency of extreme storm surges (surges greater than 0.7 m above mean sea level) has increased from 12 in 1951–1960 to 38 in 1981–1990.

The Vistula delta plain is mainly agricultural land known as the Żuławy polder district and covers about 1800 km² of low-lying land, seriously threatened by ASLR. The ‘no measures’ option thus appears to be very costly. If the current trend in SLR continues, it will become necessary to rebuild and raise the height of dikes, upgrade pumping stations and raise

polder bottoms. Existing dikes may be too low for the new hydrological conditions, especially ASLR₂ (1 m per 100 years – the pessimistic scenario). With ASLR₁ (0.3 m per 100 years – the optimistic scenario) 672 km² of land will be lost (30% of the Vistula delta plain) and with ASLR₂ – 948 km² (40%). Full protection of Żuławy polders for ASLR₂ will require the reconstruction of all existing dikes and the construction of some new ones, as well as storm and flood prevention installations. For ASLR₂ 52 km of new dikes will have to be constructed and 647 km of those presently in use upgraded. For ASLR₁, the respective numbers are 13 km and 600 km. In the worst-case scenario, i.e. for ASLR₂, salt water could penetrate the delta as far as 50 km inland. According to the present Polish regulations, dikes should be 0.7 m higher than the sea level for a storm surge with a 50-year return period. If the sea level rises by 0.3 m, the water level during 50-year storms will be too high to secure the dike-protected area for a longer period of time.

4.2. The Red River Delta

The river deltas of Vietnam are spatially the most vulnerable regions as regards the threat posed by climate change. The total area of the Red River delta plain is 16 644 km²: this is where 56% of Vietnam's rice is produced. About 73% of this land is below +10 m, 56% below +5 m and 36% below +2.5 m; 1% lies below 0 m. In addition, a significant part of the Red River delta consists of fine sediments (clay, silt and organic matter), which can easily be eroded during floods. 1302 km² of land would be lost with the ASLR₁ scenario. About 23% of the population of Vietnam lives in the Red River delta at an average density of 1010 inhabitants per km². The dominant physical impact of sea level rise will be increased flooding. Analysis of the situation in 1995 has shown that sea levels previously considered to have a return period of 1000 years now have a return period of 100 years. For the scenario of a 1 m SLR, sea levels with a 100-year return period will be +3.5 m above the MSL.

In the Red River delta plain, dikes are crucial for protecting low-lying areas against inundation. Sea dike systems are of overriding importance where shoreline defence against erosion is concerned, for instance in the Hai Hau district. Construction of new dike systems and the upgrading of old ones is a continuous process. At one of the most intensively eroded coastal segments in the Hai Hau district, the average annual coastline retreat has resulted in one line of dikes being destroyed every 10 years. Dike maintenance costs are very high and in the Hai Hau district (75% of the Hai Hau coastline is deteriorating) they represent nearly 70% of the total sea defence budget. Recent extreme floods in the Red River have a 100-year return

period (the last big flood occurred in 1971). The total area in the 100-year flood zone is about 3351 km², where flooding is defined as the inundation of land by the direct ingress of river water, either by overtopping the river banks and dikes or because the dikes have failed. Considering a 100-year return period of water levels above an MSL of 2.6 m, an expected subsidence over the next 100 years of about 0.4 m and an ASLR over 100 years of 1.0 m will result in an elevation of +4.0 m. Backflow effects and salinity intrusion can increase the upper elevation to +10 m.

5. Summary

The comparison of two river mouths representing two different climatic zones (subtropical and temperate) shows that the morphodynamics at the river-sea interface are closely dependent on the local climatic conditions and associated environmental features.

For the subtropical case, monsoons and typhoons, as well as torrential rainstorms play a key role. In addition, astronomical tides are important. In the temperate climate region, the morphological development of the river mouth depends mostly on the intensity of wave motion together with storm surges and river discharge. Ice phenomena are a further force driving the delta's evolution. The influence of ice-related processes is seasonal and manifests itself by high river discharges in early spring (snow melt), in conjunction with ice jams at the mouth. Under such conditions, the land areas of the river delta may be inundated. These physical phenomena specify the basic differences in the generation and dynamic evolution of the estuarine regions of the Red River (Ba Lat) and the Vistula. The major results of the comparison between the Red River (mainly the Ba Lat) and the Vistula deltas are summarised in Table 3.

The rate of development and the dimensions of the delta depend on the discharge of water and sediment in the river, while the evolution of the delta and geometry of the mouth is associated with wave-current motion in the coastal zone. In the case represented by the Vistula mouth, little sediment is transported to the sea and the fan-delta accumulates very slowly when the river discharge is small. Under such conditions, the evolution of the delta with its shoals and underwater channels is driven by waves and wave-induced nearshore currents. The predominant impact of wave motion on the shape of the delta becomes weaker for river discharges of about 1500 m³ s⁻¹. For discharges exceeding 2000 m³ s⁻¹, the river mouth is effectively 'flushed' and the flow capacity of the channels increases. In tropical regions, deltas most frequently consist of complex systems of shoals, periodically flooded islands and shallow water areas with wadden and marshes, intersected by

Table 3. Comparison of the Vistula and the Red River deltas

Feature	Vistula	Red River
total length [km]	1047	1149 (510 in Vietnam)
catchment area [km ²]	194 000 (87% in Poland)	169 000 (50% in Vietnam)
no. of branches: all/active	7/1	> 10/6
delta plain area [km ²]	2320	16644
mean annual rainfall [mm]	650	1740
mean annual temperature [°C]	7.5	c. 20
water discharge: min./mean/max. [m ³ s ⁻¹]	253/1080/7840	< 1000/4300/33600
mean dry/flood season discharge [m ³ s ⁻¹]	419/3840	1200/14000 (300/3500 at Ba Lat)
mean nearshore water salinity [PSU]	4–6	20–32
sediment discharge [m ³ year ⁻¹]	0.6 × 10 ⁶ –1.5 × 10 ⁶	80 × 10 ⁶ (14.5 × 10 ⁶ at Ba Lat)
mean/max. suspended sediment concentration [kg m ⁻³]	c. 0.034/0.150	1.0/5.8
meteorological and hydrological effects	seasonal moderate rainfall, ice/snow melt, ice jams, no tides, wind-driven storm surges up to 1.5 m, waves and currents	heavy seasonal rainfall, diurnal tides (from 0.5 m to 2.5 m) tidal currents (0.3–1.2 m s ⁻¹), summer and winter monsoons, typhoons, storm surges, waves
d_{50} [mm]	0.18–0.25 mm (sand) on coast far beyond estuary; 0.25–1.0 mm (sand) in the river and estuary	below 0.15 mm on coast far beyond estuary; ~0.09 mm and less (clay, organic) in the river and estuary
length of the delta coast [km]	c. 50 (5–6 at active outlet)	145 (30–40 at Ba Lat)
maximum sediment grain diameter [mm]	0.6 (1.5)	0.25
mean shoreline advance [m year ⁻¹]	5–15	30–50 (Ba Lat)
mean bottom slope	0.005–0.01	0.001–0.004
accumulation [tons year ⁻¹]	up to 2 200 000	average for last 100 years: 12 500 000 (Ba Lat)

a number of channels, the layout of which varies continually. In general, the conditions affecting delta evolution in such regions are much more complex. The predominant influence of coastal phenomena (waves, typhoons) or river phenomena (extreme discharges of water and sediment) on the estuarine morphodynamics depends on the monsoon type (season of the year). In any case, superimposed on the above impacts is the cyclic action of tides. Therefore, the longshore impact of a river mouth like that of the Vistula (20–35 km) is felt over a much smaller range than that of the Red River (150–200 km).

Compared with the Vistula, the total water and sediment discharges of all the Red River branches are about 10 and 30 times larger respectively. These differences between water and sediment discharges occur despite the smaller flow velocities in all the Red River's branches. It seems obvious that sediment grain sizes play a very significant part. The material is much finer in the Red River delta than in the Vistula. According to Pruszek et al. (2002), the grain diameters in the Red River delta vary from 0.001 to 0.25 mm, with the median grain size $d_{50} = 0.09$ mm. Only 20% of the sediment consists of non-cohesive matter. The main components are aleutic, clay and organic material. Such a composition is typical of rivers in tropical and subtropical regions. Hence, the features of river sediments are another factor reflecting the difference between estuaries located in subtropical and temperate climates. Tides are an additional factor causing an elevated (for the same river water discharge) outflow of sediments to the sea. During the ebb tide, the river discharge is magnified, which results in a cyclic daily phenomenon similar to a typical small flood wave in the river.

In relatively small river mouths with compact systems of shoals, like that of the Vistula, the major human objective is to remove the small islands and to displace the shoals as far offshore as possible. The shoals are the main reason for the occurrence of ice jams, and if the ice cover freezes to the river/sea bed, the river flow is seriously obstructed. To facilitate the outflow of water at the mouth and to maintain the outlet, groynes are constructed and gradually lengthened. This ensures that the river current is concentrated at the land-sea interface. In this way the river flushes a channel through the nearshore shoals. This method would be technically difficult to apply in a delta such as the Red River delta, where the outlets are subject to constant dynamic change, not to mention tidal processes. Very often in delta plains, there are areas of land lying below sea level that are susceptible to flooding. Irrespective of the climatic zone, this fact is of great importance in the light of the observed accelerating sea level rise. Vast deltas made up of fine sediments, located in tidal regions and subject to typhoons, like the Ba Lat delta, would seem to be particularly endangered.

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