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RECENT DEVELOPMENT OF THE VISTULA RIVER OUTLET

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Abstract. The Vistula River mouth is an unique example of river's outlet observed since the birth in 1895 to present day. There is a large documentation of morphological changes in the outlet area. In 1895, a 7 kilometres canal was dug into which the waters of the Vistula were let in. Since 1895, most of the water discharge and all sediment transport reach the Gulf through artificial channel *c*. 20 km east of Gdańsk. During the last 100 years, the shoreline has been shifted seaward *c*. 1.5 km on the eastern side, to *c* 2.5 km on the western side of the Vistula mouth. Isobath of 5 m moved seaward *c*. 3 km and isobaths of 10 and 15 m shifted 2.5 km. During the years 1895–1997, land area accreted to 3,019,000 m^2. The volume of the river-outlet cone in the year 2000 was 133.39 mln m^3 and the average rate of sediment growth over the 105 years was *c*. 1.27 mln m^3 per year.

Key words: delta front, recent delta development, Vistula River, Southern Baltic Sea, Gulf of Gdańsk, digital terrain models, remote sensing, GPS surveys.

INTRODUCTION

The Vistula River is the largest river in Poland and the second largest river in the Baltic Sea. The Vistula is 1063 km long, with 194,424 km^2 of total drainage area (54% of total area of Poland and 11.3% of Baltic catchment area). The mouth of Vistula consists of the Vistula Delta with a total area of 1,740 km^2, which is bounded by two main branches. There are also a few smaller branches within the delta. During the historical times Vistula River formed in the Gulf of Gdańsk three outlet cones (Fig. 1). Before 1840 Vistula River flowed into the sea via Gdańsk. At the end of January 1840 a large ice jam near Gdańsk was developed. A narrow dune barrier separating river bed from the Gulf of Gdańsk was broken and a new mouth was formed *c*. 10 km east of Gdańsk. The volume of accumulated sediment at the new mouth in the years 1840–1890 was about 190 mln. m^3. The shoreline at the mouth moved up to 700 m offshore (Basiński, 1995). In 1895, a new river mouth opening into the Gulf of Gdańsk was formed by excavating of a channel across the coastal dunes, *c*. 20 km east of Gdańsk. The construction of locks closed the water supply to other Vistula branches and former outlets (Basiński, 1995; Makowski,

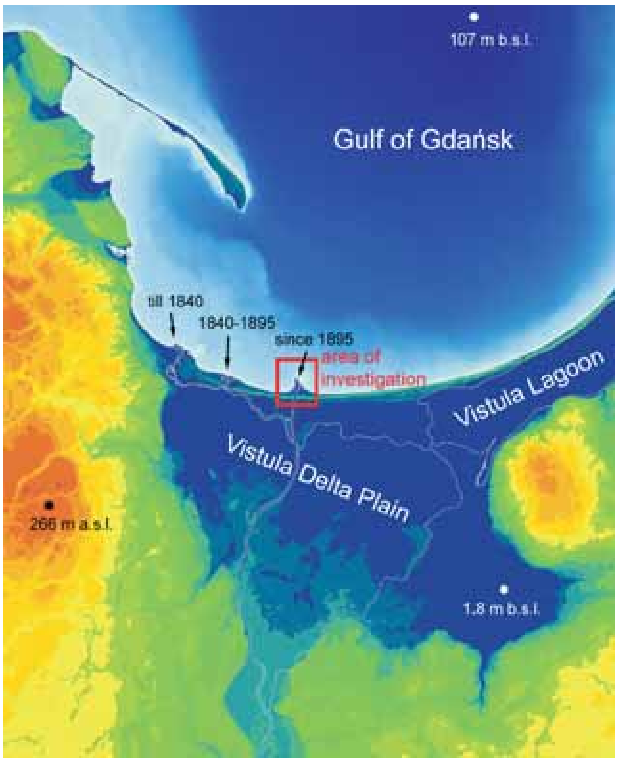

Fig. 1. Location of the investigated area and outlets of Vistula River in historical times (background map — DTM)

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1993). Since that time, most of the water discharge and all sediment transport reach the Gulf through artificial channel.

The average river flow at the mouth is 1000 m^3/s; the river discharges are 32 km^3 of water into the Baltic Sea annually on average. The maximum flows occur in March and April and reach on average *c*. 2600–2800 m^3/s. The highest flow of 8000 m^3/s was observed in June 1962. The minimum flows (on average 500–600 m^3/s occur in August, September and October (Niemirycz, 1997). Vistula is an important source of sedimentary material for the Baltic Sea especially for Gdańsk Basin. It supplies annually about 0.4 to 1.4 mln tons of bedload material and about 1.5 to 2.2 mln tons of material transported in suspension (Cyberski, Mikulski, 1976).

During the last 100 years, large quantities of sediment were deposited here, which formed the currently active front of delta and pro-delta. The sediment of the delta front form an outlet fan and develops mainly in the sand facies. The thickness of sand sediment of the river-mouth fan is maximum of 11–13 m. During the last 100 years, the shore line has been shifted seaward *c*. 1.5 km on the eastern side to *c*. 2.5 km on the western side of the Vistula mouth. Isobath of 5 m moved seaward *c*. 3 km and isobaths of 10 and 15 — 2.5 km each. In front of the outlet cone, an intensive flocculation of suspended matter was taking place in the zone of mixing the river and marine waters. The muddy-sandy sediments of pro-delta occur on the forefield of the river-mouth running at a depth zone of 12–16 m and also underlie the fan sediment (of the delta front). The thickness of this sediment ranges from 0 to about 10 m.

RESEARCH SCOPE AND METHODS

The following research was performed during the analysis of the changes which are taking place in the contemporary Vistula river-mouth:

1. Construction of digital bathymetric models for the Vistula river-mouth fan. The digital models were generated on the basis of bathymetric plans from 1894, 1933, 1970 and 2000 using ArcInfo software and natural neighbour interpolation method.

2. Analysis of aerial photographs from: 1947, 1958, 1964, 1976 and 1997. The photographs were processed using ER Mapper 6. 0 software into a orthophotomap format. The Gauss–Krüger map projection was used on a WGS-84 geocentric ellipsoid of the 1992 geographical co-ordinate system.

3. Measurements of the changes in the location of the coast line using GPS equipment were performed in October 2001, March 2002 and September 2002 using Trimble's Pathfinder ProXL equipment.

RESEARCH RESULTS

DIGITAL AREA MODELS

In 1894, the underwater coastal slope descended down to a depth of 15 m over a section of 1500 m, which gave an average bottom gradient of 1:100. In 1895, a 7 kilometres canal was dug into which waters of the Vistula were let in. In 1933, the volume of the river-mouth cone was 71,17 mln m^3 and the average rate of sediment growth over the 38 years was *c*. 1.89 mln m^3 per year. During the period 1933–1970, sediments volume in the outlet cone grew to 112.18 mln m^3 . Average rate of sediment accretion for this period decreased to 1.11 mln m^3 per year. In 2000, 105 years after the opening of the Vistula Cross-cut, volume of sediments accumulated during in the outlet cone reached 133.39 mln m^3. Between the years 1970–2000, an average accumulation rate decreased to 0.7 mln m^3 per year (Figs. 2, 3).

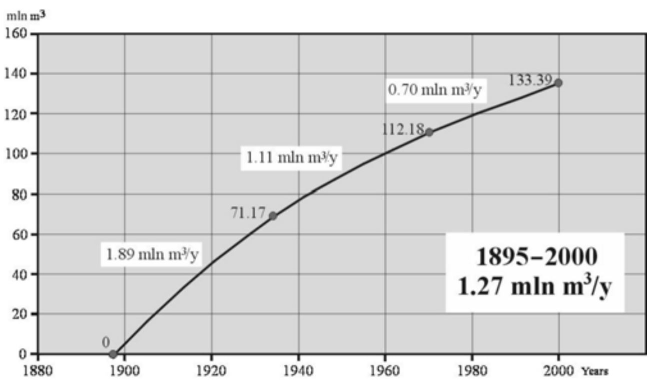

Fig. 2. The rate of accretion of Vistula outlet cone

AERIAL PHOTOGRAPHS

In order to calculate the changes in the land surface area of the Vistula river-mouth fan between 1947 and 1997, the territorial area covered by the 1997 photograph was assumed. The southerly extend is simultaneously the range of the coast line in 1894, the year before the Vistula Cross-cut was opened. The shape and the area of the fan in individual years are shown in Figure 4 and Table 1.

The average rate of land accretion for period 1895–1997 was 29,598 m^2/year but it has been varied in shorter periods (Fig. 5). The lowest rate of land grow, 12,500 m^2/year, occurred

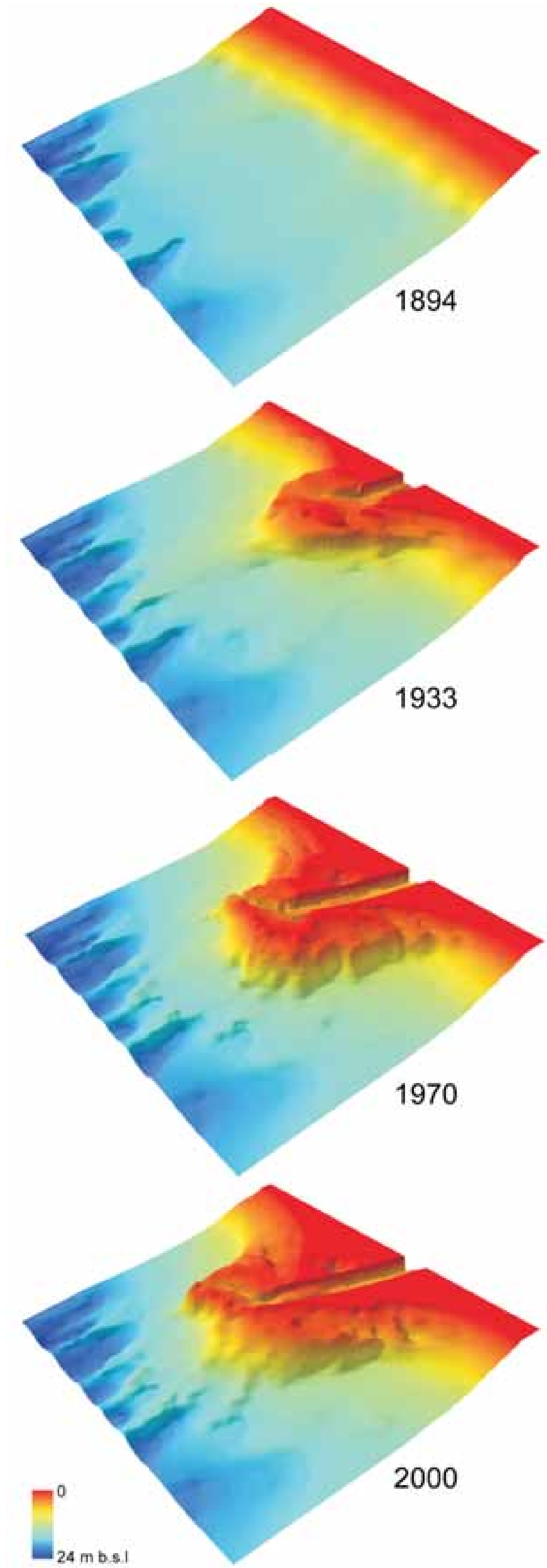

Fig. 3. Development of the Vistula outlet cone (offshore and onshore) on the basis of digital terrain models

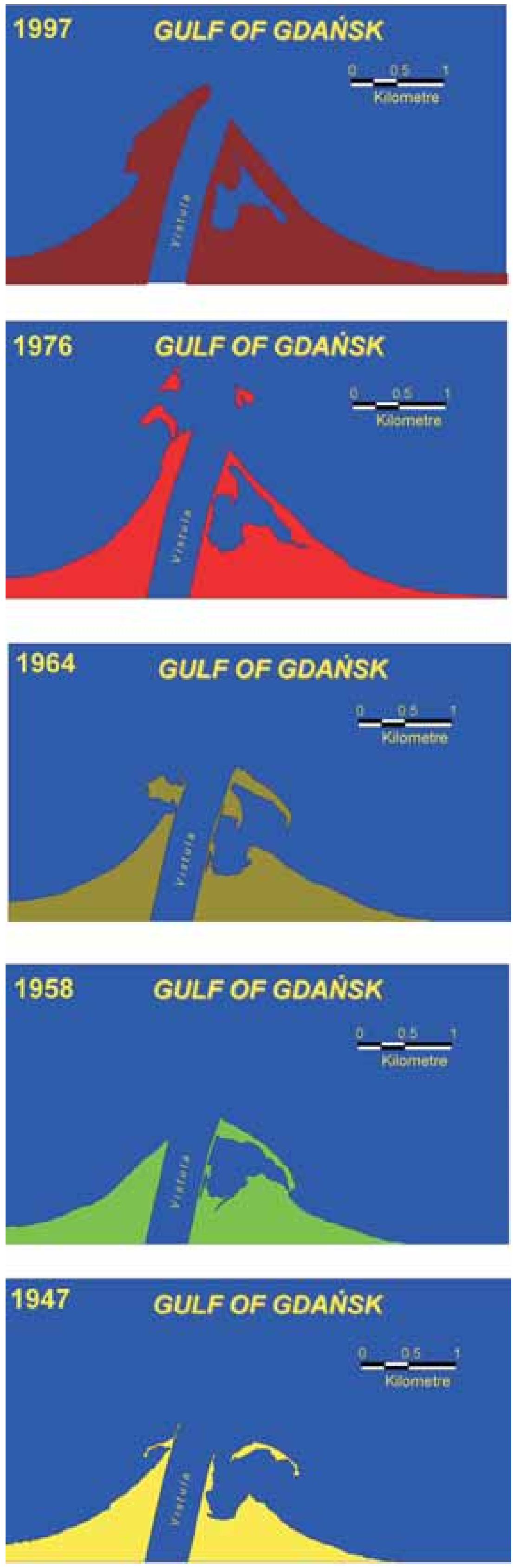

Fig. 4. Development of the Vistula outlet cone (onshore part) on the basis of aerial photos; basis of the cone – coastline in 1894

Table 1

Changes of the Vistula River outlet cone (onshore part)

Year	Area [m^2]	Period	Accreted area [m^2]	Average accretion rate [m^2/year]
1997	3,019,000	1976–1997	483,000	23,000
1976	2,536,000	1964–1976	503,000	41,900
1964	2,033,000	1958–1964	312,000	50,200
1958	1,721,000	1947–1958	138,000	12,500
1947	1,583,000	1894–1947	1,583,000	30,400
1894	0			

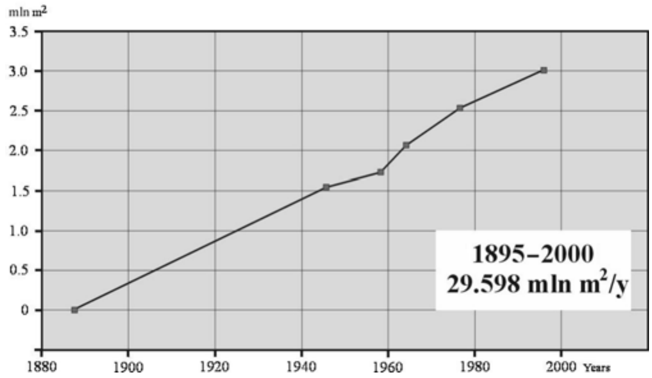

Fig. 5. The rate of accretion of onshore part of the Vistula outlet cone

between 1947–1958, and the highest — 50,200 m^2/year, between 1958–1964. The rate of the growth of the land part of the fan depended largely on the development of the piers in the river-mouth and on natural factors such as variation of the amount of rubble transported by the Vistula and marine erosion (Graniczny *et al*., 2004).

MEASUREMENTS OF THE LOCATION CHANGE OF THE COAST LINE USING GPS EQUIPMENT

The coast line and the scarps measured in October 2001 on the western side of the cross-cut receded a number of metres towards the land over 11 months. This could have been caused by the winter storms which took place in 2001/2002. The coast line on the eastern side of the river-mouth remained largely unchanged during the measurement period (Fig. 6).

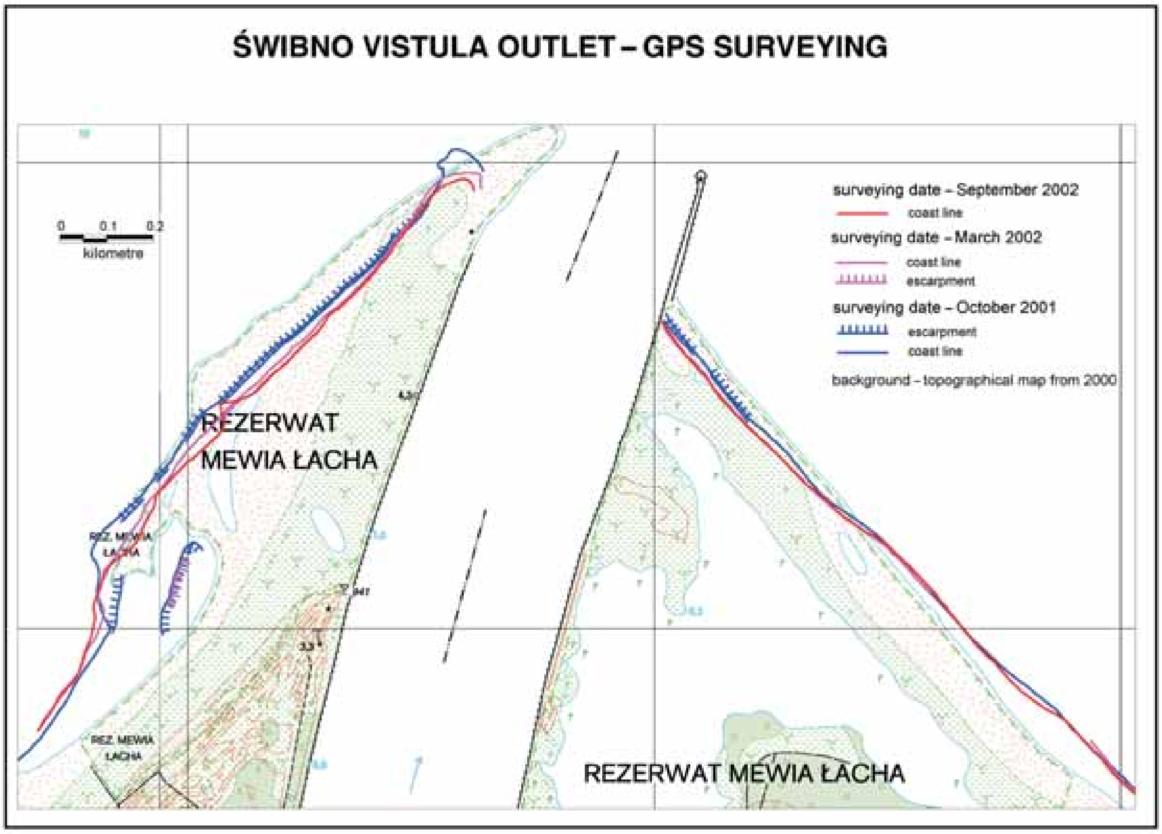

Fig. 6. Changes of the coastline in the Vistula River outlet cone in the 2001–2002, on the basis of the GPS surveying

CONCLUSIONS

The Vistula River mouth is an unique example of river's outlet observed since the birth in 1895 to present day. There is a large volume of morphological changes records in the outlet area.

Analyses of digital terrain models show that in 2000, 105 years after the opening of the Vistula Cross-cut, volume of sediments accumulated in the outlet cone reached 133.39 M m^3 and an average rate of sediment aggradations was 1.27 mln m^3/year.

According to analyses of aerial photos, the area of the land part of the outlet cone in 1997 was 3,019,000 m^2 and the average rate of land accretion for period 1895–1997 was 29,598 m^2/year.

Recently, its erosion of land part of the outlet cone is observed, mainly on eastern part (Fig. 7).

Fig. 7. Shore erosion on the western part of the Vistula river outlet cone (phot. Sz. Uścinowicz, September 2001)

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