Reports

Report on the development of the Vistula river plume in the coastal waters of the Gulf of Gdańsk during the May 2010 flood

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KEYWORDS
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Marek Zajączkowski[1,⋆]
Mirosław Darecki[1]
Witold Szczuciński[2]

[1] Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, PL–81–712 Sopot, Poland;

e-mail: trapper@iopan.gda.pl

⋆corresponding author

[2] Institute of Geology,
Adam Mickiewicz University,
Maków Polnych 16, PL–61–606 Poznań, Poland

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Abstract

The hydrological conditions, suspended matter concentrations and vertical particulate matter flux were measured as the River Vistula flood wave (maximum discharge) was flowing into the southern part of the Gulf of Gdańsk on 26 May 2010. Extending offshore for several tens of kilometres, the river plume was well stratified, with the upper layer flowing away from the shore and the near-bottom water coastwards.

1. Introduction

One of the most extensive and most damaging floods in the last 100 years occurred in May 2010 on the River Vistula, the longest river flowing into the Baltic Sea. The flood lasted for several weeks and the flood wave reached the

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river mouth on 25/26 May. The maximum river water discharge, measured at Tczew (35 km from the river mouth) on 25 May, was 6838 $m^3 s^{-1}$ (data from: www.armator.com.pl/stan_wod/Wisla/Tczew/19). For comparison, the average water discharge near the Vistula mouth is 1080 $m^3 s^{-1}$ (Pruszak et al. 2005) and has varied from 250 to 8000 $m^3 s^{-1}$ (Cyberski et al. 2006). On 26 May a research cruise on board r/v 'Oceania' was in progress to study contemporary sedimentation processes and sediments on the underwater prodelta of the Vistula. This work in the immediate vicinity of the Vistula mouth on the day when the flood reached the Gulf of Gdańsk (southern Baltic Sea) provided an unprecedented set of observations of the structure of the plume emerging from the River Vistula during a large flood. The present communication aims to document the structure and development of the flood-generated plume.

2. Methods

Sampling and measurements in the water column were carried out at eight anchored stations located on two transects along the 20 m and 30 m isobaths, at distances from 3.2 to 8.2 km from the Vistula mouth (Figure 1). The hydrological properties of the water were measured with a Mini CTD Sensordata SD 204, the data being interpolated by the Kriging

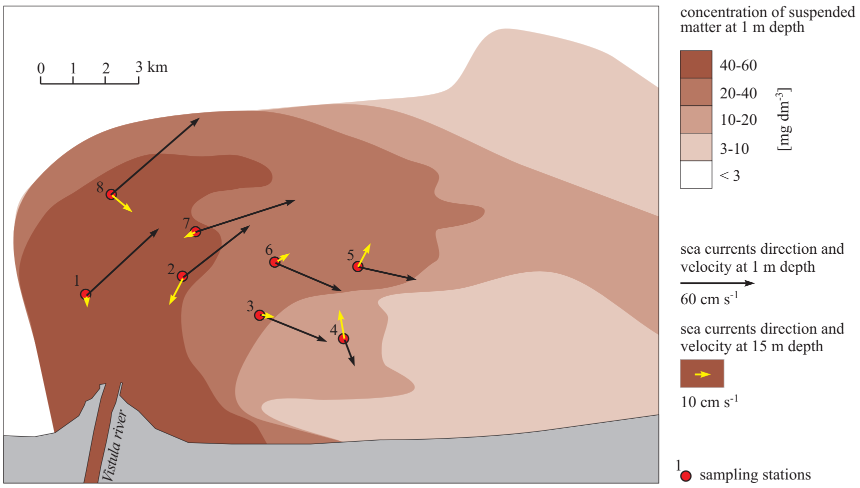

Figure 1. Anchored sampling stations during the r/v 'Oceania' cruise on 26 May 2010. The concentration ranges of surface suspended matter were plotted from satellite images from MODIS (Moderate Resolution Imaging Spectroradiometer) on board the Aqua and Terra satellites and calibrated by empirical data. Sea currents were measured with a Sensordata SD 6000 current meter at 1 m and 15 m depths

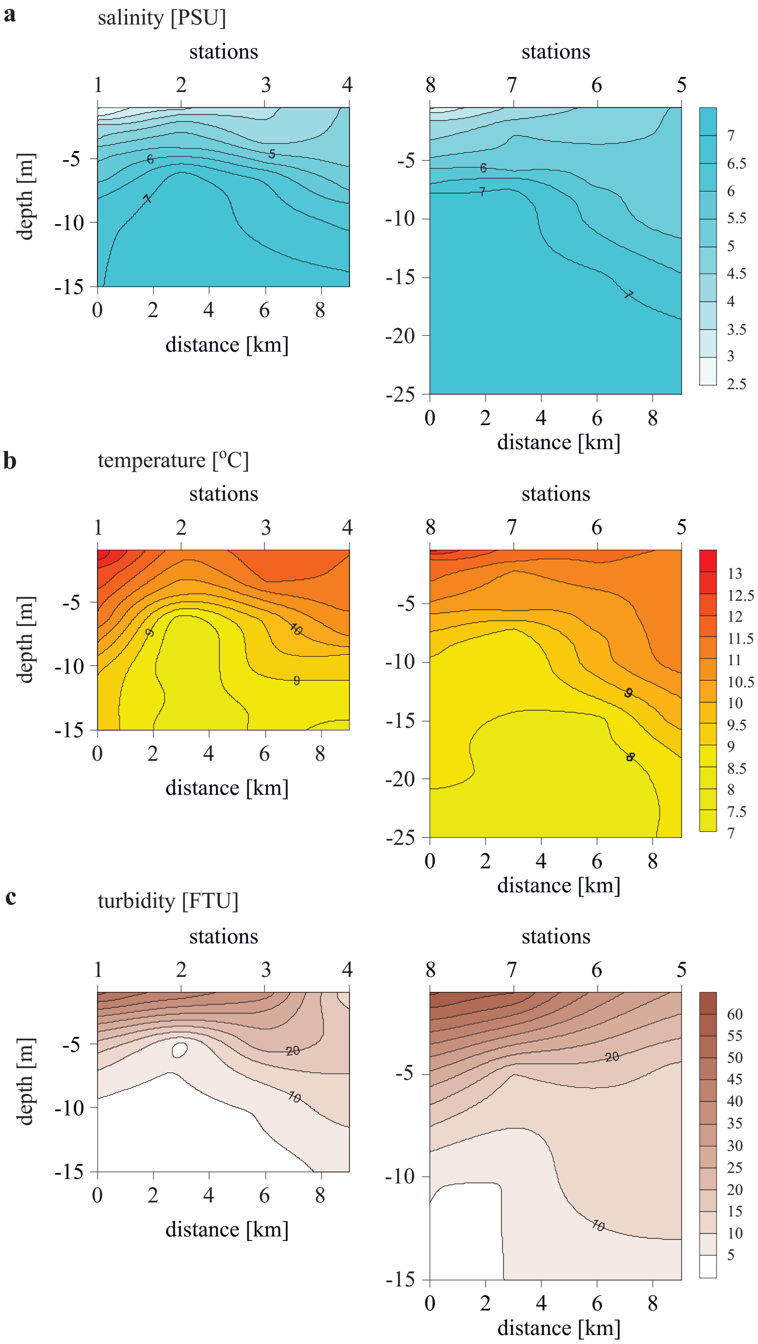

Figure 2. Water salinity [PSU] (a), water temperature [°C] (b) and water turbidity [FTU] (c) on two transects along the 20 m and 30 m isobaths on 26 May 2010. Data interpolated by the Kriging method

Table 1. Sea currents and water turbidity in Formazin Turbidity Units (FTU) measured at the standard depths on 26 May 2010

Station	Latitude [°N]	Longitude [°E]	Turbidity [FTU]	Current velocity [cm s^{-1}]	Current direction [°]	Water depth [m]
1	54.38738	18.93551	51.4	54.2	48	1
1	54.38738	18.93551	18.6	12.4	52	5
1	54.38738	18.93551	3.7	2.2	130	10
1	54.38738	18.93551	2.6	3.4	176	15
2	54.39286	18.98064	43.1	62.2	52	1
2	54.39286	18.98064	3.9	8.6	128	5
2	54.39286	18.98064	3.9	6	184	10
2	54.39286	18.98064	3.7	6	208	15
3	54.38189	19.01998	37.7	10.2	112	1
3	54.38189	19.01998	23.8	4	103	5
3	54.38189	19.01998	5.7	3.6	132	10
3	54.38189	19.01998	2.7	2.8	100	15
4	54.37634	19.0636	11.0	13	156	1
4	54.37634	19.0636	17.7	9.4	148	5
4	54.37634	19.0636	13.0	8.2	328	10
4	54.37634	19.0636	6.6	7.4	348	15
5	54.39456	19.06545	29.0	20.6	104	1
5	54.39456	19.06545	12.4	9.8	28	5
5	54.39456	19.06545	14.1	11	52	10
5	54.39456	19.06545	7.3	7.8	28	15
6	54.39654	19.02673	38.6	35	113	1
6	54.39654	19.02673	17.1	5.6	84	5
6	54.39654	19.02673	15.0	4.4	93	10
6	54.39654	19.02673	6.7	7.2	57	15
7	54.40513	18.98758	55.3	50.2	73	1
7	54.40513	18.98758	14.7	9.8	81	5
7	54.40513	18.98758	5.3	5.8	248	10
7	54.40513	18.98758	5.4	3.6	244	15
8	54.41625	18.94738	61.0	66.8	49	1
8	54.41625	18.94738	28.9	30.8	32	5
8	54.41625	18.94738	5.7	3.8	100	10
8	54.41625	18.94738	3.2	8.2	128	15

method (see Figure 2). Current direction and velocity as well as water turbidity were measured with a Mini SD 6000 Sensordata current meter and a Seapoint turbidity meter. Water samples were collected in 5 l Niskin bottles from depths of 1 m, 5 m, 10 m and 15 m (Table 1). Double cylindrical sediment traps with an opening surface of 0.004072 m^2 and a length of 1 m (Zajączkowski 2002) were deployed for 8 hours, 3 m above the bottom at station 2. Subsamples from the Niskin bottles and sediment traps were vacuum-filtered onto pre-weighed

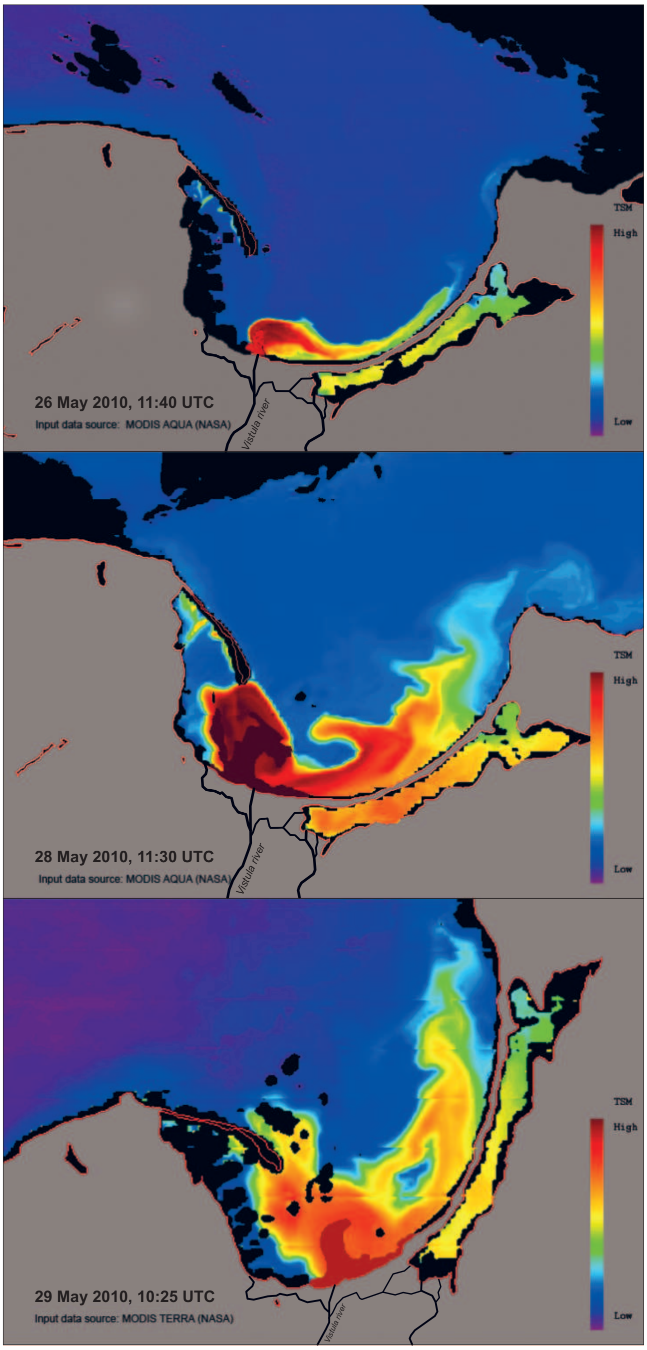

Figure 3. Spatial distribution of the TSM derived from MODIS Aqua and Terra satellite images on 26, 28 and 29 May 2010. The colour scale on the right-hand side is in relative units (see text for details)

MN GF 5, 0.4 μm pore size filters and rinsed with distilled water. The filters were dried at 60°C for 24 h and reweighed to obtain the dry mass. Next, the filters were combusted at 450°C for 24 h and weighed to obtain the organic fraction of the particulate matter (weight loss). The empirical data of solid concentrations show that the backscattering signal in Formazin Turbidity Units (FTU) gives the concentration of suspended solids (in mg dm^{-3}) accurate to 10%.

Satellite images from MODIS (Moderate Resolution Imaging Spectroradiometer) on board the Aqua and Terra satellites were acquired to investigate the Vistula outflow (Figure 3). The MODIS ocean colour data were processed using SeaDAS data analysis software. With the SeaDAS high resolution processing scheme, maps were produced with an enhanced spatial resolution of 250 m. The spatial distribution of Total Suspended Matter (TSM) was calculated from the water-leaving radiance at 547 nm. The episodic nature of the event with such an extremely high concentration of TSM and the lack of sufficient in situ samples to verify the algorithm for the retrieval of TSM concentration precluded the making of maps with reliable absolute TSM values; the figures therefore present only relative values. Despite the above limitations, the spatial distribution visible on the images does provide useful and valuable information for this study.

3. Results and discussion

The satellite images showed that the plume on 26 May extended from the river mouth up to 25 km northwards and 60 km eastwards. The measured surface salinity dropped to 2 PSU at the mouth of the Vistula (stations 1, 2, 7 and 8), and the influence of the freshwater input was detectable down to 5 m. The bottom water salinity reached 7 PSU. The surface water temperature varied from 10 to 14°C, decreasing to 8°C in the near-bottom layer (Figure 2). Water turbidity was greatest 1 m beneath the surface at stations 1, 2, 7 and 8, varying from 50 to 60 FTU. Empirical suspended matter concentration data from station 2 yielded respective values of 49.2, 9.6 and 3.4 mg dm^{-3} at 1 m, 5 m and 15 m depths. The contribution of organic matter to the suspended matter reached 30% at the surface and 40% near the bottom. The particulate matter flux to the bottom at station 2 was 35 g m^{-2} d^{-1}, but only 8% of this flux was due to the sedimentation of organic matter. The settled sediments were composed of fine sand ($>30\%$) and silt fractions.

The surface currents (1 m depth) were strongest at the stations near the river mouth (1, 2, 7, 8), varying from 50 to 60 cm s^{-1}; all were flowing NW and NWW. Below the surface plume, the currents were flowing back towards the river mouth (Figure 1). The surface currents at the stations located to the east of the river mouth were flowing E and SEE.

The spatial distribution of the TSM concentration from the very first day of the flood outflow (26 May), visible on the first satellite image, shows a very strong gradient in TSM values at the outflow boundary, which indicates that in the vicinity of the river mouth the fresh riverine water did not mix with the sea water (Figure 3). The much denser sea water pushed the river outflow aside, towards the E or SEE. After two days (see the satellite images from 28 May) the area of flood outflow had extended, but the still strong gradient at the outflow boundary, especially in the N and NNW direction, indicates a separation of these two water systems. A different situation is visible on the satellite image from the fourth day of the flood outflow (29 May). The visibly smoother transition between the riverine plume and sea water can be related to two processes: 1) the beginning of mixing between those two water systems, and 2) the deposition of a significant part of the suspended matter entering the Gulf of Gdańsk.

The data show that during a large river flood, a plume is formed in the southern Gulf of Gdańsk; the water column stratification, surface and near-bottom currents flowing in opposite directions, the high suspended matter concentrations and the vertical particulate matter flux resemble fjord-like estuarine conditions.

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