Revealing the influence of various factors on concentration and spatial distribution of suspended matter based on remote sensing data

Olga Yu. Lavrova[a]*, Dmitry M. Soloviev[b], Marina I. Mityagina[a],
Alexey Ya. Strochkov[a], Tatiana Yu. Bocharova[a]
[a]Space Research Institute RAS, 84/32 Profsoyuznaya Str., Moscow, Russia
[b]Marine Hydrophysical Institute, 2, Kapitanskaya, Sevastopol, Crimea

ABSTRACT

The paper discusses the results of a research on the influence of various hydrometeorological factors on distribution of suspended matter carried by rivers into the sea. The research is based on remote sensing data received in different bands of electromagnetic spectrum. Suspended matter concentration and integral water turbidity were estimated based on data from MODIS, MERIS, ETM+, TM and OLI sensors. The study was performed for two regions with very different characteristics: the semi-enclosed Gulf of Gdańsk of the Baltic Sea and eastern part of the Black Sea. It is shown that the plume fraction with highest suspended matter concentration of the lowland River Vistula spreads primarily under the impact of wind. Low concentration plume fraction is driven by the longshore current. In case of extraordinary floods, turbid Vistula waters spread in the upper sea layer almost all over the Gulf. The situation in the eastern part of the Black Sea with its narrow shoal and abrupt shelf edge wherein flow highly turbid mountain rivers is quite different. Here, the dominating role is played by runoff. Its intensity determines both plume shape and dimensions. A strong easterly wind can change plume configuration, cause formation of jet-like plumes.

Keywords: river plume, suspended matter, coastal zone, satellite observations, Black Sea, Baltic Sea, Landsat, Envisat.

1. INTRODUCTION

Increase of suspended particulate matter concentration in the shelf zone is caused primarily by river outflows carrying sediments into the sea. Fluvial sediments are associated with many important problems such as coastal erosion, beach formation, anthropogenic pollution of the sea, etc. Today, they are particularly acute as the retreat of coasts due to low sedimentation rate appears irreversible in conditions of world ocean level rise, while coastal pollution of many seas reaches dangerous levels[1]. Obviously, the total amount of sediment brought by the rivers to their mouths is not equal to the amount of suspended matter contributed to seawater as a result of the inflow because considerable part of the sediment is deposited on the seabed.

Inflow of suspended and dissolved terrigenous matter into the sea and its subsequent transport over the coastal zone is a complex and multifaceted process whose investigation demands considering many factors. A wealth of literature is devoted to the problem, most of the authors emphasize regional peculiarities pertaining to certain river, river mouth and sea factors, as well as geography characteristics of the coastal zone[2,3,4]. Numerical modeling of suspended matter inflow and transport is in the focus of the studies[3,5,6]. This requires testing and verification of the models. Rapid development of satellite remote sensing techniques and relatively easy access to the data for the past decade facilitate investigations of suspended matter over large aquatic bodies in different seasons.

The paper examines applicability of satellite remote sensing data of optical range for investigating the impact of various factors on the distribution of suspended matter in the coastal zone. To assess the informative value of products derived from satellite data, they were compared with in situ measurements conducted in the southeastern part of the Baltic Sea in the regions of the Vistula River mouth. Another study region is the eastern part of the Black Sea where a large amount of suspended solids is carried into the sea by multiple mountain rivers.

*olavrova@iki.rssi.ru; phone +7 495 333-4256; fax +7 495 333-1056

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2. STUDY REGIONS

We discuss the impact various factors have on concentration and transport of suspended matter in two regions: the Gulf of Gdańsk and eastern Black Sea. The two regions differ significantly in geography and hydrometeorological conditions.

2.1 The Gulf of Gdańsk

The Gulf of Gdańsk is located in the southern part of the Baltic Sea. Its northern border is a line extending between Cape Rozewie and Cape Taran of the Sambian Peninsula (Figure 1, left). Average depth of the Gulf of Gdańsk proper is 70 m. The water of the Gulf is significantly impacted by river outflows from the River Vistula. The Vistula (Pol. Wisła), the largest Polish river, is 1047 km long. It originates in the West Beskid range of the Carpathians, South Poland, and flows to the Gulf of Gdańsk on the Baltic Sea. The two main branches of its estuary are the Nogat, which flows past Malbork to the Vistula Lagoon, and the Martwa Wisła (dead Vistula), which flows past Gdańsk. The mean annual flow rate is 1081 m^3/s. Since the end of 19th century, the Vistula has entered the Gulf of Gdańsk directly through an artificial channel. This direct inflow without transitional estuary causes the water masses to mix in the Gulf. Depending on the wind and the currents, the two water bodies can mix vigorously, creating dynamic water fronts or broken off portions of riverine waters moving into the Gulf as freshwater plumes.

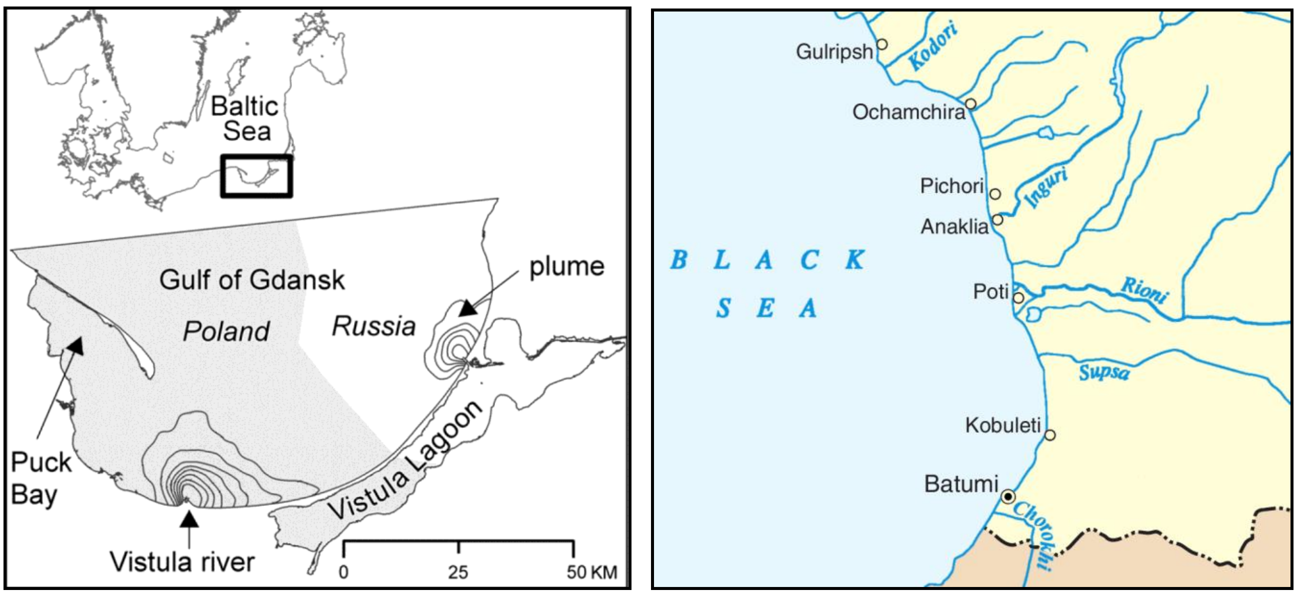


Figure 1. Study areas. Left: The Gulf of Gdansk. Grey color marks Polish part. The isolines show typical plume patterns [7]. Right: Main rivers flowing into the eastern Black Sea.

Currents are determined by winds, and can vary even on short temporal and small spatial scales[8]. Current direction and intensity are strongly related to wind direction, duration and speed and to shoreline shapes. Currents flow parallel to the shore in shallow coastal zones, and current velocities in these zones are frequently less than 50 cm/s. Surface and bottom currents are equally dependent on winds, but their directions and velocities can differ distinctly.

From field observations it is known that in case of wind from west, north and east the riverine water cannot spread easily in the Gulf, so it spreads along its coast. In case of northeastern wind the water moves westwards, while in case of northwestern wind eastwards. Wind from south and southwest allows free spreading of the riverine water in the Gulf. It is also well known that weak winds (not exceeding 2-3 m/s) facilitate spreading of the riverine water, whereas strong wind induces mixing close to the river outflow.

Available statistics[9] indicate that east- and northeastward spreading predominates in time (50%), while northward spreading accounts for about 25%, and 16% of time the water spreads at both sides of the river outflow. Seasonal changes in river outflow rate have a direct influence on seasonal salinity changes, especially in surface layer of coastal regions.

Density currents are also observed in the Gulf of Gdańsk. They are induced by a non-uniformity of water density. The density difference in the Baltic Sea occurs mainly due to water mass exchange with the North Sea; however in the Gulf of Gdańsk the main cause of density differences is Vistula River inflow. Density currents are weaker than those of wind origin, nevertheless they cannot be neglected[10].

2.2 The eastern Black Sea

The Black Sea is among the most thoroughly examined marine basins on earth. However, some processes, including transport and spreading of suspended matter in the coastal zone, demand further attention. In the past years, the ecological situation in the sea has aggravated mainly due to increased pollution inflicted in particular by coastal runoff. Cargo shipping and oil production and transportation have developed to dominate in the economics of the sea. Existing ports are expanding; construction of new ones is planned. Meanwhile, the Black Sea is a very important tourist and recreation area. All this is true for the eastern part of the sea where the coast is divided between Georgia and Turkey. In the study region, over 10 big mountain rivers flow into the sea. The major inflow is attributed to (north to south) the Kodori River, Eristkali Channel (also regulating the flow of the Inguri River), rivers Khobi, Rioni, Supsa, and Coruh (Figure 1 right); the biggest are those of Rioni and Coruh.

The Coruh (or Chorokhi in Georgian) River watershed is located at the border between Turkey and Georgia. The river originates in the Mescit Mountain Range (highest peak 3255 m) in Turkey and flows into the Black Sea in Batumi, Georgia. Its total length is 431 km: 410 km in Turkey, 21 km in Georgia. Mean annual outflow is 6.824 km^3, annual sediment load is 5.8 million m^3. About 85% of the total annual outflow falls within a three-month period of May to July[1].

Rioni is the largest water body in western Georgia. Its length is 327 m, total watershed area is up to 13,400 km^2. The river originates from two sources on the southern side of the Main Caucasian Range, crosses the Colchis Lowland and flows into the Black Sea near a city of Poti via a delta. The main part of the river water (up to 90%) flows into the sea over a channel built in 1939 to protect Poti from floods. Mean annual outflow is 12 km^3, sediment load is 6.9 million m^3. Water level increases in spring (April) and reaches its maximum in June. The flooding continues until the end of August. In the end of September the flooding is caused by heavy rains (annual air humidity is as high as 70-83% by Poti meteo station data) and reaches its maximum in October – November. Minimum water level is observed during December - February. Mean outflow rate at the mouth is 405 m^3/s. Water suspended matter load is high (up to 2650 g/m^3 in spring)[11].

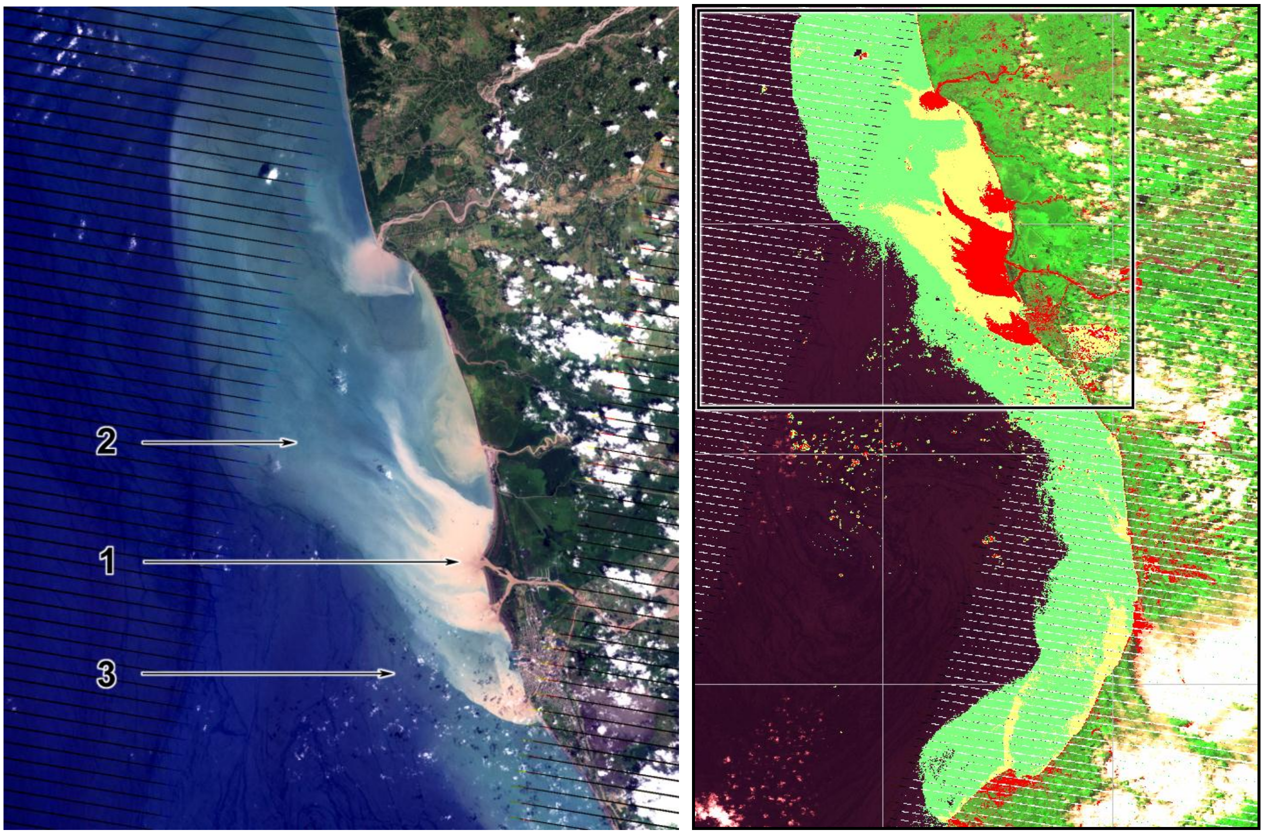
Bottom topography of the eastern Black Sea is characterized by a narrow offshore shoal that shrinks north to south. In the north, a 50 m isobath is located 7 km off the coastline, whereas it almost approaches the coast near a town of Kobuleti in the south (Figure 9). Another peculiarity of bottom topography is a large number of canyons. Several canyon groups and isolated canyons are located between the mouths of rivers Mzymta and Coruh. Most canyons have their heads at depths of 15-25 m, some others are incised into the coastal zone with abrupt edges located already at depths of 6-10 m. The floor slopes range 6–20^o, sometimes steep benches are encountered, the side wall slopes reach 45^o, but can be near vertical as well. The canyons extend down to depths of 1000 m. They play an important role in sediment distribution, over 2000 thousand m^3 of coarse-grained sediments are trapped by the canyons and transported to great depths. The greatest amount of beach-forming sediments sinks in the Coruh Canyon[1].

3. DATA AND METHODS

The research was conducted on the basis of satellite data obtained from the following sensors: Landsat-5 TM, Landsat-7 ETM+, Landsat-8 OLI, Envisat MERIS/ASAR and Terra/Aqua MODIS. Landsat data were downloaded from the free-access archive at http://glovis.usgs.gov/. The data were used to compile color composites of a 30 m spatial resolution. MERIS and ASAR data were provided by the European Space Agency in the framework of several scientific projects. Spatial resolution of MERIS color composites was 260 m, of ASAR images – 25 and 150 m.

Terrigenous waters carried by rivers enter the sea in river plumes forming mesoscale structures with sharp boundaries. Within the plume, not only salinity and temperature are different from seawater, but also turbidity is higher due to increased content of suspended particulates and dissolved organic matter[4]. Each river carries an individual range of particulate solids typical of its own watershed which helps identifying the boundaries of its outflow plume.

True-color composites of visible satellite data are best suitable for discrimination of sea areas with different optical properties, associated in our case with different suspended matter concentration. In high resolution true-color images of a river plume, three main areas can be detected. The first one is adjacent to the river mouth and contains the largest part of the inflow sediments comprised of sand (> 0.1mm); silt (0.001 - 0.01mm) and clay (< 0.001mm). The main portion of the suspended solids settles down out of the river flow in a "sandfall". The closer to the river mouth, the greater are the intensity and particle size of the sandfall. In true-color images, the first area has colors ranging from grey and beige to dark brown. The second area, bordering the first one, contains fine aleuritic and politic non beach-forming fractions and has yellow-green to light-green colors. The third area can extend for great distances without distinct boundaries. This is the area covered by a film comprised of surfactant pollutants brought by the fluvial inflow (Figure 2a).



a b

Figure 2. a) Arrows point at three areas with different water turbidity in a fragment of Landsat-7 ETM+ true-color composite of July 08, 2005, 07:45 GMT; b) Classification of the same true-color composite into 3 classes by water turbidity; rectangular frame shows location of the fragment in Figure 2a.

For the most illustrative cases, we selected synchronous images of Landsat and Envisat MERIS. Their true-color composites permit only qualitative assessment of concentration of suspended matter in water. Quantitative estimates of total suspended matter (TSM) and chlorophyll-a concentrations were performed using Envisat MERIS data by standard NASA algorithms adjusted to the regional conditions. To raise the estimate accuracy of TSM concentration maximal and minimal limits, maps of two types were compiled: a detailed map with a scale ranging 0 to 30 g/m^3 and a less detailed map with a scale ranging 0 to 60 g/m^3. For the river outflow areas in the eastern part of the Black Sea (Figure 3), TSM concentration was estimated at 30 to 50 g/m^3 for the first area, 13 to 18 g/m^3 for the second area, and 5 to 12 g/m^3 for the third area. Also, sea surface temperature charts were compiled from Aqua/Terra MODIS and Landsat data to determine the plume areas.

Landsat data processing was performed using a toolkit provided by the See the Sea (STS) portal developed in the Space Research Institute of the Russian Academy of Sciences (Moscow, Russia). The system is designed for investigating various processes and phenomena in ocean and sea using different satellite data[12,13]. STS gives researchers tools to work with both remote sensing data and results of their analyses. The key feature is the possibility to perform complex analysis of data varying in physical character, spatial resolution and units of measurement. STS specialized software enables processing and analysis of optical data, including:

- easy-to-use spectral bands selection and visualization;
- assessment of spectral bands informative content;
- composition of various true-color images;
- sequential conjugation of information derived from different bands;
- spectral radiance and spectral reflectance graph drawing for selected spatial points;
- water surface type classification;
- specialized data products.

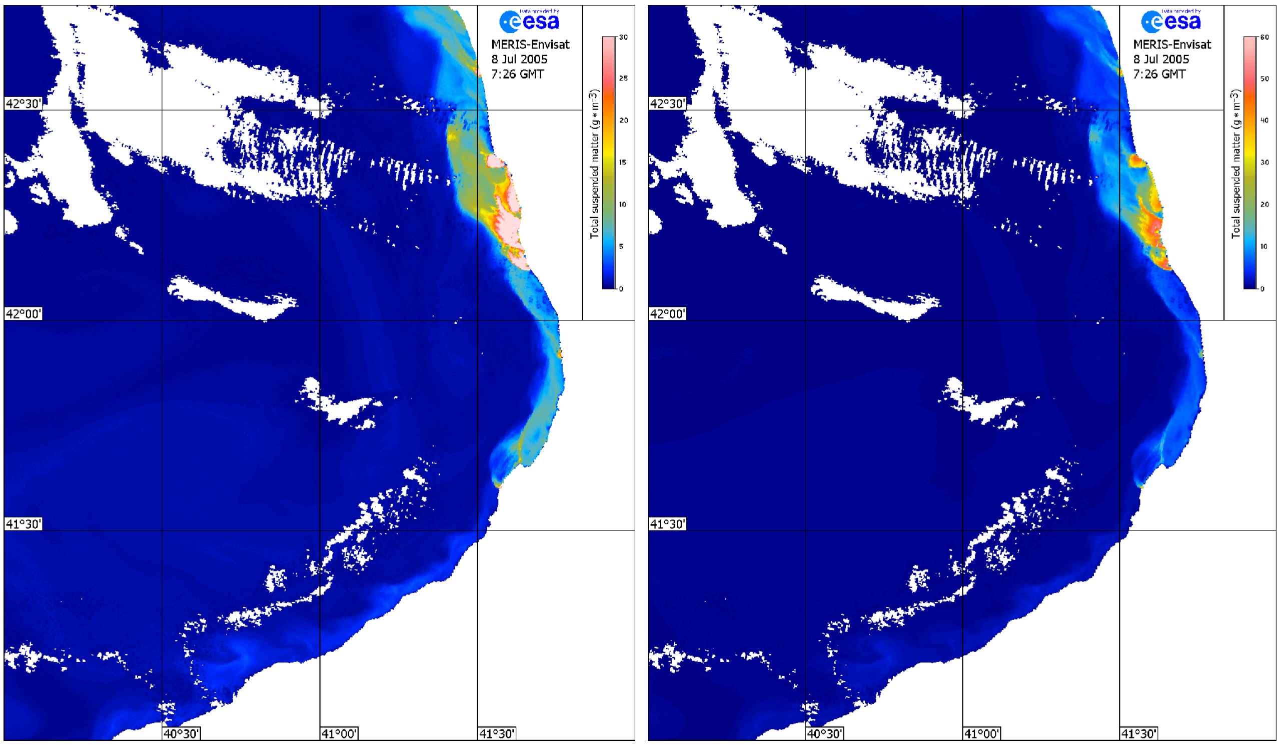


Figure 3. TSM concentration maps compiled for two different scale ranges/intervals from Envisat MERIS image of the same date as in Fig. 2. The time difference between the acquisitions of the Landsat-7 ETM+ and Envisat MERIS images is 19 min.

The classification toolkit of STS enables complex processing of a satellite image to divide it into classes according to preset parameters. This can be used for highlighting particular image features and mapping. Supervised and unsupervised classification methods are available. The algorithms are taken from GRASS GIS[14]. In this work, we used an unsupervised method consisting of two stages: signature calculation and maximum likelihood classification. The method is based on automatic clustering by the spectral likelihood criterion. All pixels with close spectral characteristics are united in the same class. The number of classes to be identified is set by the user. River plume classification into 3 areas (classes) by turbidity was performed as follows. First, a classification into 7 classes was performed, as a rule attributing the same class to areas of turbid waters. Next, this class was further classified into 3 (sub)classes. The obtained result agrees well with the pattern observed in the true-color image (Figure 2b). Area size of each class and total plume area were estimated.

The main focus of this work is transport of suspended matter brought into the Black Sea by mountain rivers on its eastern coast. All Landsat data from the region (Path 172; Row 31, glovis.usgs.gov) for 2000-2014 were analyzed. In that period, the imaging was performed by Landsat-5 TM (2000, 2002-2003, 2006-2007, and 2009-2011), Landsat-7 ETM+ (2000-2014) and Landsat-8 OLI (2013-2014). Total 295 images were obtained. Approximately half of them featured river plumes, in the others clouds precluded observation. Figure 4 shows image number breakdown by years and informative value. True-color composites were compiled and classified for all cloudless and low cloud images. In total, 144 images were processed. Note, for each month of each year there are images carrying information on river plumes (Figure 4). Such baseline dataset implies statistically significant processing results.

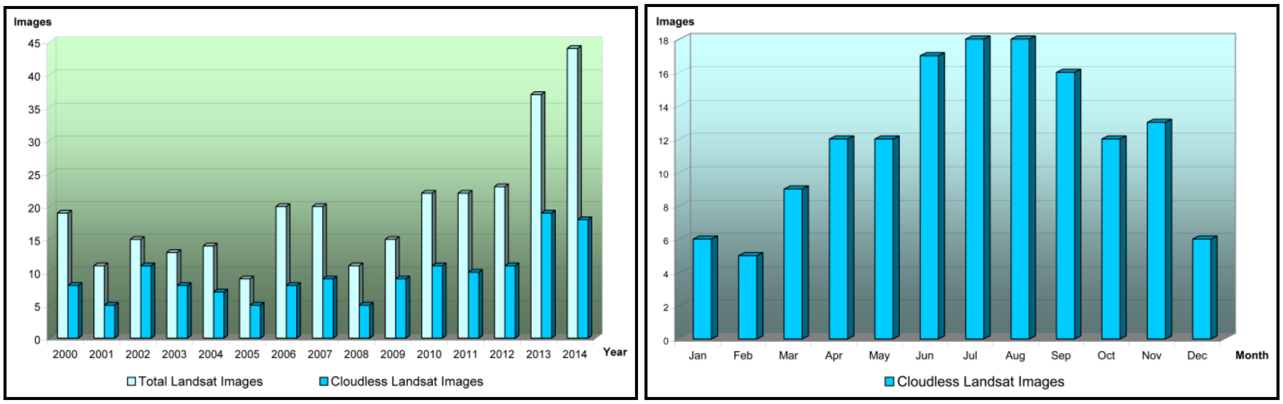


Figure 4. Eastern Black Sea Landsat dataset: (left) number of total and cloudless images by years; (right) average number of cloudless images by months.

Joint analysis of satellite and meteorological data was performed in STS to reveal the impact of wind and precipitation on the transport of suspended matter in the coastal zone. The wind and precipitation data were taken from the NCEP Reanalysis archive. Data from coastal meteo stations were also used to ensure better understanding of hydrometeorological conditions.

4. RESULTS

The main factors influencing the transport of suspended matter taken to the sea by rivers are runoff, tide, offshore coastal current, seabed topography and wind forcing[2,3]. Tidal activity in the Baltic and Black Seas is rather weak and can be neglected for the purposes of our study. Let us consider spreading characteristics of suspended matter in the Gulf of Gdańsk and eastern Black Sea.

2.1 Spreading of suspended matter in the Gulf of Gdańsk

Factors influencing the transport of suspended matter discharged into the Gulf of Gdańsk by the Vistula River were investigated for the case of one of the most extensive and most damaging floods in the past 100 years occurred in May 2010. The flood lasted for several weeks and the flood wave reached the river mouth on 25/26 May. The maximum river water discharge was 6838 m^3/s [15]. For comparison, the average water discharge near the Vistula mouth is 1080 m^3/s [16]. Aftermaths of that gigantic outflow were observed for at least two weeks. By lucky coincidence, on 26 May satellite imaging of the Gulf of Gdańsk was performed by a number of sensors: Envisat MERIS and ASAR, Landsat-7 ETM+ and Terra/Aqua MODIS. Moreover, most importantly for correct satellite data interpretation, on the same day a research cruise of r/v Oceania was in progress to study 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 Gdansk provided an unprecedented set of observations of the structure of the plume emerging from the River Vistula[15].

The in situ data were collected on 26 May. Figure 5a presents a fragment of Landsat-7 ETM+ image of that data indicating locations of sampling stations. The contact measurements were compared with the satellite data. On 26 May the scene was partially covered by clouds (Fig. 5) making any quantitative comparison impossible. In spite of the change in plume configuration occurred between 26 and 28 May, the situation near the river mouth, where sampling stations were placed, did not change much. So, a comparison of the in situ turbidity values taken at 1 m depth horizon on 26 May and turbidity values derived from MERIS TSM concentration of 28 May showed agreement within the accuracy of less than 10%. The impact of wind on spreading of the plume during the period from May 26 to June 18, 2010 was considered. It was established that Class 1 and 2 waters with high suspended matter concentrations spread in the upper sea layer (for such turbiduty, values of TSM concentrations reflect water condition down to 1 m depth) under the impact of wind, while Class 3 waters almost always moved parallel to the coast driven by a cyclonic longshore current (Fig. 6).

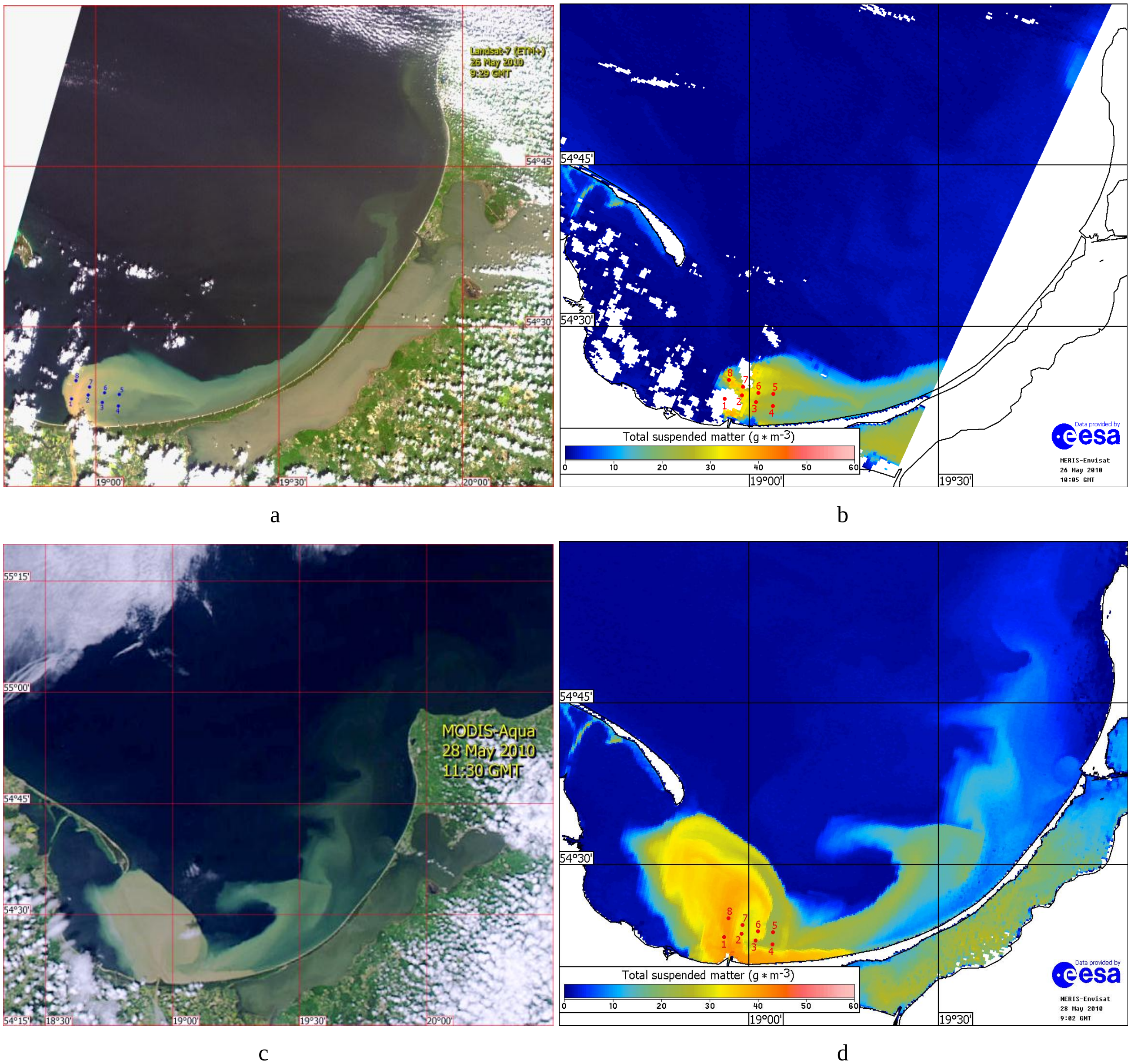


Figure 5. Spreading of Vistula plume in the Gulf of Gdańsk during the extensive flood on 26-28 May 2010. a) Landsat-7 ETM+ true-color composite of May 26, 2010, 09:29 GMT; b) TSM concentration map from Envisat MERIS image of May 26, 2010, 10:05 GMT; c) fragment of MODIS Aqua true color composite of May 28, 2010, 11:30 GMT; d) TSM concentration map from Envisat MERIS image of May 28, 2010, 09:02 GMT. Numbers indicate locations of sampling stations.

Interestingly, the plume grew in size during 26-30 May, clouds covered the region from May 31 to June 3, and in the images of 4-5 June turbid waters appeared only in the immediate vicinity of the mouth. Heavy rainfall that followed caused another runoff and a new plume emerged with TSM concentration of up to 50 g/m^3. The new plume also moved under the impact of wind that changed almost every day (Figure 6).

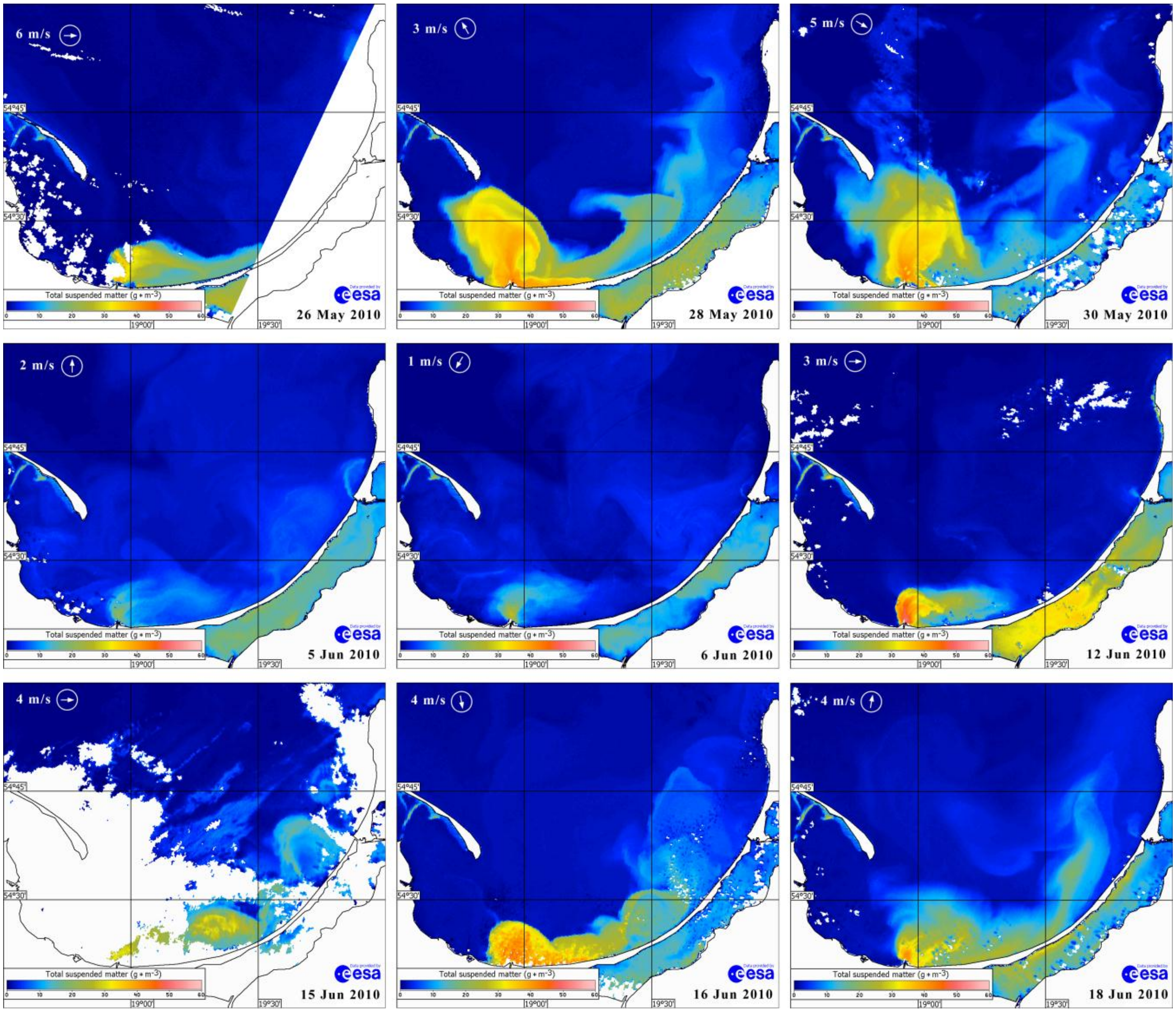


Figure 6. Impact of wind on suspended matter distribution. A series of TSM concentration maps based on Envisat MERIS data for the period from 26 May to 18 June 2010. Arrows indicate wind direction.

2.2 Factors influencing concentration and spreading of suspended matter in the eastern Black Sea

Analysis of the whole satellite dataset has shown that river plumes out of Rioni, Khobi and Supsa are observed in all visible images, irrespective of the season of the year. This is explained by a two-way runoff formation, by precipitation and glacier melt, characteristic of the rivers. In the Colchis Lowland, where they flow, rainfall intensifies in summer and autumn months. Seasonal variation in suspended matter content is observed in the sea areas adjacent to the river mouths (area 1, Figure 2). Based on Envisat MERIS data, mean TSM concentration is estimated at 40 g/m^3 with peak values of around 60 g/m^3 in July and October. The plume of River Coruh has distinct seasonal features. During snowmelt in the mountains from March to June, an increased TSM concentration of 35-40 g/m^3 is observed. The next rise in suspended matter quantity is registered in November and December in association with heavy precipitation. In the other periods of the year, the Coruh plume is either invisible in satellite images or appears similar to area 3 in Figure 2; TSM concentration does not exceed 8-10 g/m^3.

In the coastal zone of interest, river plumes spread mostly to the right from river mouths along the coastline and parallel to isobaths, i.e. northwards. This completely agrees with modeling[5,17,18]. The Black Sea Rim Current has the same direction in this region and obviously certain effect on plume spreading and suspended matter transport. Longshore streamflows of suspended matter are observed under westerly winds predominating in this region. Under strong easterly winds, the streamflows turn perpendicular to the coastline carrying suspended matter far to the open sea at distances over 30 – 50 km (Figure 7).

Figure 7. Fragment of a true-color image of the eastern part of the Baltic Sea acquired by ETM+ Landsat-7 on 15 November, 2000, shows up to 50 km long jet-like plumes.

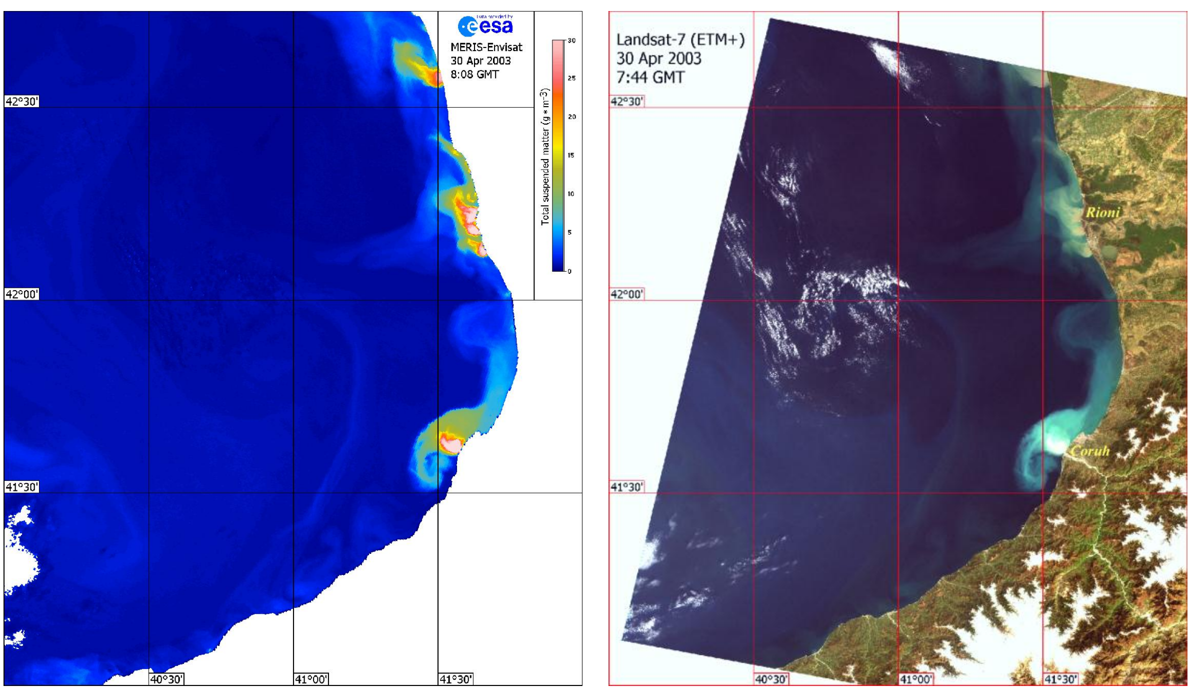


Figure 8. Coruh River plume in the shape of eddy dipole in (left) TSM concentration map from an Envisat MERIS image of 30 April, 2003, and (right) true-color composite of Landsat-7 ETM+ obtained 26 minutes before the Envisat MERIS image.

Of particular interest is Coruh River plumes in the shape of eddy dipoles. The physics of this phenomenon is explained in Batchelor's monograph[19] as a puff of fluid through the open end of a tube, producing a vortex ring which travels away from the hole. Such dipoles are observed in April - May and November – January periods (Figure 8). As a rule, they are asymmetric with a distinct cyclonic part of 8-10 km in diameter and rather blurred and much greater anticyclonic part reaching 40 km in diameter. The asymmetry is most likely associated with prevailing plume spreading to the right from the river mouth. Beside longshore streamflows and dipoles, we also detect plumes in the shape of isolated cyclonic eddies or jets as long as 50 km (Figure 7).

Mapping of suspended matter in the coastal zone and calculating the size of areas of highest TSM concentration is a crucial task. It was solved on the basis of image classification results. Area size estimates were derived for Class 1 and 3 areas. The maximal size of Class 1 area (closest to mouth, highest TSM concentration) is 175 km^2. Such size is typical for March – April and some days in November featuring peak values of sediment load carried to the sea by all the rivers. Maximal total spreading area of suspended matter observed in the April – May period amounts to 2200 km^2 (Figure 9).

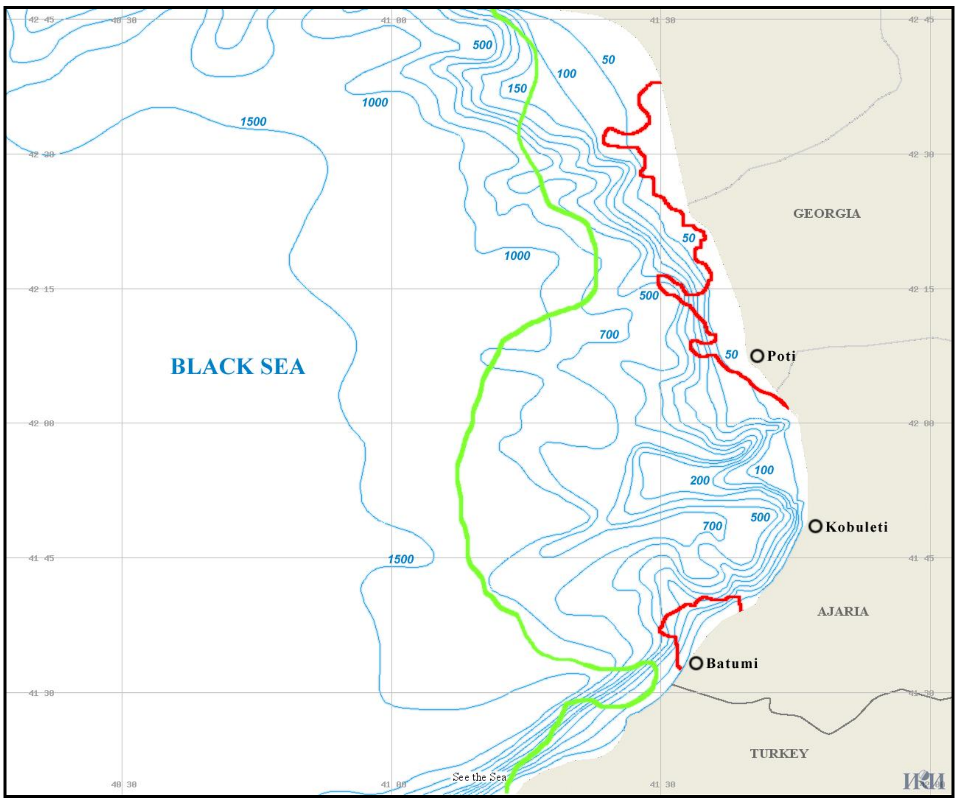


Figure 9. Areas of maximal spread of suspended matter in the eastern Black Sea: green curve marks the boundary of Class 3 area; red curve the boundary of Class 1 area, according to satellite image classification based on suspended matter patterns.

5. CONCLUSION

The influence of various factors on concentration and distribution of suspended matter brought into sea by rivers was investigated for two regions with very different characteristics. The lowland River Vistula flows into the semi-enclosed Gulf of Gdańsk with mean depth of 70 m. Its plume fraction with highest suspended matter concentration spreads primarily under the impact of wind. Low concentration plume fraction is driven by the longshore cyclonic current. In case of extraordinary floods, similar to the one occurred in the end of May 2010, turbid Vistula waters spread in the upper sea layer almost all over the Gulf. According to our multiyear satellite observations, during seasonal floods the impact of wind on the distribution of suspended matter is also significant.

The situation in the eastern part of the Black Sea with its narrow shoal and abrupt shelf edge wherein flow highly turbid mountain rivers is quite different. Here, the dominating role is played by runoff. Its intensity determines both plume shape (for instance, Coruh eddy dipoles) and dimensions. A strong easterly wind can change plume configuration, cause formation of jet-like plumes. The affect of the Rim Current is not evident from the analysis of available data. It can be responsible perhaps for spreading of Class 3 plume fraction (plume surface film component) to the north along the coast.

Comparison of suspended matter concentrations derived from satellite data and contact measurements demonstrated the need for further improvement of the algorithms estimating suspended matter concentration from satellite data. A number of Russian researchers have progressed remarkably in this direction[20].

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