On river plumes along the Turkish coast of the Black Sea

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Abstract
Heavy rains have become a serious problem for the coastal zone of the Krasnodar Territory of the Russian Federation and the Black Sea coast of Turkey. They lead to a significant increase in water levels in rivers, flooding of villages and even large cities, damage to urban and tourist infrastructure, roads and railways, bridges, beaches, flushing of garbage and sewage into rivers. This leads to environmental problems and even loss of life. River runoff forms river plumes in the coastal zone of the sea, which, depending on wind speed and direction, speed and direction of coastal currents, river runoff and density difference with sea water, can have various forms and spread in different directions from the mouth of the river, as well as participate in mesoscale and sub-mesoscale circulation of coastal waters. River plumes significantly affect the quality of sea water and the sanitary and epidemiological situation on the beaches of the resort area of Krasnodar Territory and Turkey. The situation is aggravated by the fact that sewage systems are in poor condition in cities or are completely absent in most of small villages along rivers and the coastal zone. After heavy rains, wastewater very often reaches the sea and poses a serious threat to human health. The purpose of this study is to use satellite remote sensing to demonstrate the behavior of river plumes along the Black Sea Turkish coast.

Key words: the Black Sea, Turkish coast, rivers, river plumes, heavy rains, remote sensing, satellite optical imagery.

Introduction

In the Black Sea, about 80% of the total river runoff enters the northwestern part of the sea, where the Danube brings 201 km³/year, the Dnieper - 52 km³/year, the Dniester - 10 km³/year, the Southern Bug - 2 km³/year, and Ingle - 0.2 km³/year. In total, the rivers of the northwestern part discharge to the Black Sea about 270 km³/year. The rivers of the Caucasian coast bring about 43 km³/year, small streams at the Crimean Peninsula give about 4 km³/year, and small streams at the Bulgarian-Romanian coasts give about 3 km³/year.
The runoff of Turkish rivers is estimated at about 25 km³/year in which western part constitutes 9.93 km³/year and eastern part 14.9 km³/year, where the Kızılirmak brings 6.48 km³/year, the Sakarya – 6.4 km³/year, the Çoruh – 6.3 km³/year, the Yeşilırmak – 5.8 km³/year (Simonov, Altman, 1991; Bulgakov, Yurkova, 2000; Jaoshvili, 2002; Goryachkin, Ivanov, 2006; Kostianoy, Kosarev, 2008; Kosarev et al., 2008; Mikhailov, Mikhailova, 2008; Grinevetskiy et al., 2015). According to different papers published in 1977-2019 the Black Sea freshwater runoff is estimated in the range between 338 km³/year (Simonov, Atman, 1991) and 517 km³/year (Margat, Treyer, 2004), while a mean value derived from these publications is of 401 km³/year (Poulos, 2019). Rivers play a key role in the state of coastal environment bringing water and sediments to the sea. Nutrient and pollutants concentrations in coastal waters, as well as shelf sedimentation, coastline evolution, and benthic ecosystem are mostly associated with river runoff (Poulos, 2019).

Heavy rains have become a serious problem for the coastal zone of the Krasnodar Territory of the Russian Federation and the Black Sea coast of Turkey (Fig.1). They lead to a significant increase in water levels in rivers, flooding of villages and even large cities, damage to urban and tourist infrastructure, roads and railways, bridges, beaches, flushing of garbage and sewage into rivers. This leads to environmental problems and even loss of life. So, for example, on August 8, 2002, the city of Novorossiysk and the nearby resort area Shirokaya Balka were flooded as a result of heavy rain. In the flooded area, more than 100 people died. On July 6-7, 2012, according to the Russian Hydrometeorological Center, the equivalent of five-month precipitation (275 mm) fell overnight in Krymsk, Novorossiysk and Gelendzhik (Fig.1). One hundred and seventy-one people died during the flood, which damaged houses of almost 13,000 people and affected nearly 30,000 people. The flood was a part of the consequences of a severe storm that struck the Krasnodar Territory, which resulted in almost six months of rainfall in two days in the region, and it was the largest in the past 70 years. Heavy rains caused dangerous floods on the rivers, including a catastrophic flood on the Adagum River near the city of Krymsk. The total damage is estimated at 20 billion Rubles (300 mln USD). Such heavy rains occur annually, for example: on September 7-8, 2018, when heavy rains hit the entire coastal zone from Adler to the Kerch Strait; on October 23-25, 2018, when heavy rains destroyed roads and railways and bridges in the Tuapse region; on June 24, 2019, when heavy rains caused landslides and damaged roads and tourist infrastructure in the mountain resort region of Krasnaya Polyana near Adler; on June 29, July 16, July 25, 2019, when heavy rains again hit and flooded the city of Sochi; on July 27, 2019 Gelendzhik was flooded; on August 17, 2019 Sochi and Lazarevskoe were flooded by heavy rains; on September 6, 2019 Khosta region of Sochi was flooded and landslides damaged roads; on September 17, 2019 again heavy rain hit Sochi, Khosta and Adler (Fig.2).
massive landslides caused by heavy rains destroyed buildings in Ordu Province (Fig.3); on June 18, 2019 flash floods and landslides hit Trabzon Province; on July 11, 2019, heavy rains were registered in Samsun and Giresun; on July 17-18, 2019 flash floods and landslides hit Düzce Province in western part of the Turkish coastal zone; on August 4, 2019 floods hit Rize Province; on August 8, 2019 tons of harvested hazelnuts flow into the Black Sea after floods in Ordu Province; on August 17, 2019 heavy rains triggered floods in Istanbul which is very often affected by heavy rains (Fig.4); on August 26, 2019 a bridge in Terme, Samsun Province, collapsed after heavy rain (Fig.1). Recently, on October 21, 2019 a person was killed in the flood in Eynesil District of Giresun. We note that in all these cases heavy rains occurred in summer time, when there is a seasonal minimum of atmospheric precipitation over these coastal zones of the Black Sea. At the same time, this is a highest tourist season in Russia and Turkey, and heavy rains seriously affect coastal tourism.

Figure 2. Satellite view of heavy rains, which on September 17, 2019 hit Sochi, Khosta and Adler, as well as coastal zone of Abkhazia and Georgia. Source: https://worldview.earthdata.nasa.gov.

Figure 3. Satellite view of heavy rains, which on May 15, 2019 caused massive landslides, which destroyed buildings in Ordu Province. Source: https://worldview.earthdata.nasa.gov.
River runoff forms a river plume in the coastal zone of the sea, which, depending on the speed and direction of the wind, the velocity and direction of the coastal currents, the amount of runoff and the density difference with sea water, can have different shapes and can spread in different directions from the mouth of the river, and also participate in mesoscale and sub-mesoscale circulation of coastal waters (Osadchiev, 2013; Osadchiev & Zavialov, 2013; Zavialov, Makkaveev, 2014; Zavialov et al., 2014; Kostianoy et al., 2016; Lavrova et al., 2011, 2016; Zavialov, Zatsepin, 2018). River plumes significantly affect the quality of sea water and the sanitary-epidemiological situation on the beaches of the resort area of the Krasnodar Territory and Turkey. The situation is aggravated by the fact that sewage systems are in poor condition in cities or even absent in most of the small villages located along rivers and coastal zones. After heavy rains, sewage very often reaches the sea and poses a serious threat to human health. For the eastern part of the Black Sea coast of Turkey, this problem is even more acute, because this region of Turkey is characterized by a maximum of atmospheric precipitation (for example, 1300 mm/year in Giresun).

The aim of our research is to study the relationship between the amount of runoff of major rivers along the Russian and Turkish Black Sea coasts and the area of the corresponding river plumes. Our preliminary studies of Russian Mzymta and Sochi river plumes using MERIS Envisat satellite data on the concentration of total suspended matter (TSM) for 2006-2011 and data on river discharge at gauging stations showed that there is a clear linear relationship (correlation coefficient R = 0.99) for the Mzymta River and a parabolic dependence (R = 0.98) for the Sochi River (Fig. 5) between river runoff and river plume area (Lebedev et al., 2019). The obtained results require confirmation on a wider statistical material. The study of a larger number of Black Sea rivers in Russia and Turkey will allow us to establish existing dependencies and understand the causes of various types of regressions that describe the relationship of river runoff and plume area. In any case, the obtained relationships, even if they may be specific for each river, will greatly help to estimate the area of river plumes and identify coastal areas that are exposed to environmental risks after heavy rains. Moreover, in those cases when gauging stations are located at a considerable distance from the mouth of the river, for example, the Krasnaya Polyana gauging station on Mzymta, the obtained dependences can be used to forecast the area of river plumes with an advance of 12-24 hours.

The purpose of this paper is to demonstrate the capabilities of satellite remote sensing in the detection of river plumes along the Turkish coast of the Black Sea, which will be used for further analysis of the relationship between the runoff of the main Turkish rivers and the area of the corresponding river plumes.
Data and Methods

To show different cases of river plumes behavior along the Turkish coast of the eastern Black Sea, we used satellite imagery from MERIS (MEedium Resolution Imaging Spectrometer, spatial resolution 260 m) of Envisat (2011), OLI (Operational Land Imager, spatial resolution 30 m) and Thermal InfraRed Sensor (TIRS, spatial resolution 100 m) of Landsat-8 (2017, 2018), and MSI (MultiSpectral Instrument, spatial resolution 10-20 m) of Sentinel-2A (2017, 2018). The water processor from Free University of Berlin (FUB/WeW) (Schroeder et al., 2007a,b) embedded in the MERIS Envisat processing software, and recommended by European Space Agency (http://step.esa.int/main/toolboxes/sentinel-3-toolbox/s3tbx-features/), was used to calculate the concentration of the Total Suspended Matter (TSM) in absolute values (g m⁻³).

Results

The examples of river plumes along the coast of Turkey are given in chronological order to show their different behavior resulted from rains of different intensity and affected by mesoscale and sub-mesoscale water dynamics in the coastal zone. Some comments are given directly in captions for Figures 6-22.

Conclusions

Numerous studies of river plumes in the Black Sea did not set up the task of establishment of a relationship between river flow at gauging stations and the area of the resulting river plume in the sea. Solving such a problem by numerical methods should not present great difficulties, however, it is obvious that the result obtained will be applied to all rivers equally, i.e. the dependence of the plume area on the flow of the river will be the same. Our preliminary studies aimed at obtaining this dependence for the Mzymta and Sochi rivers at Russian coast of the Black Sea based on data from gauging stations and satellite images of river plumes showed that they are significantly different for the same range of river discharge. For the Mzymta River, we obtained a linear dependence with a correlation coefficient of 0.99, and for the Sochi River, a parabolic dependence describes better this relationship which significantly differs from the Mzymta River (Lebedev et al., 2019).
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Figure 6. Spatial distribution of TSM (g m$^{-3}$) derived from MERIS Envisat on 14 January 2011, 07:38 GMT. The coastal zone from Samsun to Giresun is covered by high concentration of suspended matter (yellow and red colors) which is entrained in two anticyclonic eddies and transferred offshore at a distance of 50-100 km. Coastal and offshore waters in the southeastern most part of the Black Sea is free from turid waters.

Figure 7. Spatial distribution of TSM (g m$^{-3}$) derived from MERIS Envisat on 17 March 2011, 08:06 GMT. The coastal zone from Sinop to Giresun is covered by high concentration of suspended matter which is entrained in three anticyclonic eddies and transferred offshore at a distance of about 30 km. Eastward of Giresun there are small coastal spots of turbid waters. The highest TSM concentrations and areas of turbid waters are observed in the coastal zone of Georgia.
Figure 8. Spatial distribution of TSM (g m$^{-3}$) derived from MERIS Envisat on 8 May 2011, 08:00 GMT. The coastal zone from Sinop to Trabzon is covered by a narrow band of high concentration of suspended matter which is associated with a coastal current. The area eastward of Trabzon is covered by clouds (white colors).

Figure 9. Spatial distribution of TSM (g m$^{-3}$) derived from MERIS Envisat on 16 May 2011, 08:07 GMT. The coastal zone from Sinop in Turkey to Batumi in Georgia is covered by high concentration of suspended matter which is entrained in a dozen of sub-mesoscale cyclonic eddies of about 10-20 km, and transferred offshore by jets at a distance up to 80 km in the eastern part.
Figure 10. Spatial distribution of TSM (g m\(^{-3}\)) derived from MERIS Envisat on 27 May 2011, 08:03 GMT. The whole coastal zone from Sinop to Batumi is covered by a narrow strip of clouds which hides spatial distribution of TSM. The southeastern part of the Black Sea is characterized by a presence of a large dipole vortical structure of about 150 km, which redistribute turbid waters on a large aquatoria. The highest concentrations of TSM are observed in the coastal zone of Georgia.

Figure 11. Spatial distribution of TSM (g m\(^{-3}\)) derived from MERIS Envisat on 10 June 2011, 07:51 GMT. The coastal zone from Sinop to the border with Georgia is characterized by a series of spots with high concentration of suspended matter, from which plumes of more turbid waters propagates northeastward. A spectacular jet of turbid waters starts from the area of Rize and forms a 150 km large anticyclonic eddy in the eastern part of the sea.
Figure 12. Spatial distribution of TSM (g m\(^{-3}\)) derived from MERIS Envisat on 23 June 2011, 08:14 GMT. The coastal zone from Sinop to Batumi is covered by a narrow band of high concentration of suspended matter (some areas are hidden by clouds). In the eastern part of the sea there are two jets of turbid waters more than 120 km long. The easternmost jet forms an anticyclonic eddy.

Figure 13. Turbid waters (light colors) on optical image of MSI Sentinel-2A on 18 October 2017, 08:20 GMT. The coastal zone from the airport Ordu-Giresun (white runway strip in the western side of the image) to Görele at the eastern side of the image displays turbid waters associated with every river mouth, and river plumes directed in the northeast direction. In the eastern part of the image jets transport turbid waters 15-30 km offshore.
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Figure 14. Spatial distribution of TSM (g m$^{-3}$) derived from MSI Sentinel-2A on 18 October 2017, 08:20 GMT (see Fig.13). TSM reaches 25-30 g m$^{-3}$ near river mouths. The largest river plume is observed near the Harşit River mouth (38°51’E).

Figure 15. Turbid waters (light blue colors) on optical image of OLI Landsat-8 on 19 October 2017, 08:08 GMT. The largest river plume persists from the Harşit River mouth.
Figure 16. Spatial distribution of TSM (g m$^{-3}$) derived from OLI Landsat-8 on 19 October 2017, 08:08 GMT (see Fig.15). TSM reaches 20 g m$^{-3}$ near the Harşit River mouth and its river plume is more than 25 km long.

Figure 17. Spatial distribution of sea surface temperature (SST, °C) derived from TIRS Landsat-8 on 19 October 2017, 08:08 GMT (see Figs.15, 16 for optical images). Coastal sea waters are warmer than 16°C (yellow and red colors), but mountain rivers bring colder waters which are displayed by dark blue spots at every river mouth where temperature is of 13-15°C.
Figure 18. Turbid waters (light colors) on optical image of MSI Sentinel-2A on 28 October 2017, 08:20 GMT. Small river plumes are observed in the western side of the image.

Figure 19. Spatial distribution of TSM (g m\(^{-3}\)) derived from MSI Sentinel-2A on 28 October 2017, 08:20 GMT (see Fig.18). TSM is of 3-4 g m\(^{-3}\) near all river mouths.
Figure 20. Turbid waters (light blue colors) on optical image of OLI Landsat-8 on 15 May 2018, 08:07 GMT. The largest river plume is observed from the Harşit River mouth.

Figure 21. Spatial distribution of TSM (g m\(^{-3}\)) derived from OLI Landsat-8 on 15 May 2018, 08:07 GMT (see Fig.20). TSM reaches 30 g m\(^{-3}\) near the Harşit River mouth.
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Figure 22. Spatial distribution of sea surface temperature (SST, °C) derived from TIRS Landsat-8 on 15 May 2018, 08:07 GMT (see Figs.20, 21 for optical images). Coastal sea waters are characterized by SST of 17°C (green colors). Mountain rivers bring colder waters which are displayed by dark blue spots at every river mouth where temperature is of 14-15°C.

The present study, based on the analysis of satellite optical imagery of moderate and high spatial resolution, showed different behavior of river plumes along the coastal zone of Turkey in the Black Sea. It is evident that riverine turbid waters with high concentration of suspended matter can be involved in vortical motion by coastal anticyclonic and cyclonic mesoscale and sub-mesoscale eddies, which can transfer turbid waters up to 150 km offshore. Thus, it was shown that coastal eddies have an important impact on the behavior of river plumes in the sea, and consequently on the ecological state of the coastal zone which is very important for local tourism in Turkey.

Since 2018, a team of partners from the P.P. Shirshov Institute of Oceanology (Moscow), the Geophysical Center (Moscow), the Marine Hydrophysical Institute (Sevastopol) of the Russian Academy of Sciences, and Giresun University (Giresun, Turkey) conducts joint research on river plumes in the Black Sea coastal zone of Turkey using satellite methods. Turkish colleagues contributes to this study with field measurements of the quality of river and coastal waters in the eastern Black Sea, in particular, acrylamide contamination of water and bottom sediments, which is an extremely toxic substance, a carcinogen that affects the nervous system, liver and kidneys (Tepe, 2016; Tepe, Aydin, 2017; Ustaoğlu, Tepe, 2019; Tepe, Cebi, 2019; Tas et al., 2019). It was first discovered in food in 2002, since then, the Food and Agriculture Organization and the United Nations World Health Organization have devoted particular attention to studies of acrylamide in food and the environment.

The goal of our collaborative study is to establish statistically valid dependences of the river plume area on the river discharge for the main Black Sea rivers of Russia and Turkey based on satellite data on suspended matter and data on river discharge at gauging stations. To achieve this goal it is necessary to test the methodology for determining the area of river plumes for as many rivers as possible in Russia and Turkey with a different set of characteristics of basic parameters (catchment area, discharge at hydrological stations, the cross-sectional area of the river in the vicinity of the gauging station, the cross-sectional area, width and depth of the river mouth, the configuration of the coastline of the sea near the river mouth, bottom
topography on the shelf, offshore water dynamics, turbidity of riverine water, and others). In addition, field measurements of river plumes and the chemical composition of its waters are extremely important for assessing the degree of environmental hazard for the local population using the beaches of the Black Sea.

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