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MARINE PHYSICS

Estimating the Deposition of River-Borne Suspended Matter from the Joint Analysis of Suspension Concentration and Salinity

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Abstract—A simple method has been proposed for estimating the deposition and mixing rates of river-borne suspended matter and mapping the deposition intensity in near-estuary sea areas. The method involves the joint analysis of data on the total suspended solids (TSS) concentration and salinity. The relative content of river runoff in seawater is determined from the salinity value. If the suspended matter is subject to deposition, its concentration would be fully determined by the relative content of river water in the seawater and could be calculated based on salinity. However, the factual TSS concentration is usually lower than that estimated from salinity, because of deposition. Hence, the amount of TSS deposited from a specific water parcel can be obtained as the difference between the concentration prescribed by the linear mixing of river and seawater masses and the factual concentration. This scheme has been implemented using high-resolution data collected in field campaigns in the Black Sea near the Mzymta River mouth. The TSS concentration was obtained using ultraviolet fluorescence lidar, and salinity was measured by a pump-through CTD system.

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INTRODUCTION

Knowledge of the mechanisms and quantitative parameters of the transport and deposition of river sediment and allochthonous terrigenous suspended matter in nearshore sea is essential for a number of engineering and scientific problems. A large body of publications deal with the transport of suspended matter, and any reference list would be incomplete. The main tendencies in the sedimentation and transport of suspended matter in the ocean were first generalized by Lisitsyn [4] in the second half of the 20th century.

However, the practical calculation of the deposition and mixing of river-borne suspended matter in specific nearshore areas under actual hydrometeorological and oceanological conditions remains an extremely complex problem. Traditional methods involving the selection and analysis (including particle-size analysis) of samples are very laborious. In addition, these cannot reach a high spatial resolution, although the spatial variability of suspended matter in nearshore regions is realized within hundreds or even tens of meters in many cases, especially for small rivers.

We cannot consider ourselves experts in the transport of suspended matter. However, we have obtained high-resolution data on the total suspended solid (TSS) concentration in the nearshore region of the Black Sea at the mouth of the Mzymta, the largest river in the Russian sea sector, where we have performed environmental monitoring studies over several years. Data on suspended matter were obtained via the underway remote sensing with an ultraviolet fluorescence lidar providing a spatial resolution of several meters. Simultaneous underway flow-through conductivity–temperature–depth (CTD) measurements were also performed, which provided data on surface salinity with a spatial resolution of several tens of meters. We propose to combine the high-resolution data on TSS concentration and salinity. As will be shown below, this approach makes it possible to acquire quantitative estimates and judge the spatial distributions of the deposition and mixing of allochthonous suspended matter in the area under study, as well as to attempt revealing the relationships of these processes with hydrometeorological conditions.

INITIAL DATA

Calculations were performed using data obtained in three expedition of the small research vessel *Ashamba* in the region between the Mzymta and Kudepsta river estuaries from May 26 to 29 of 2010, from May 25 to 30 of 2011, and from May 16 to 19 of 2012. All the expeditions were made in the same season, under similar river flood conditions. Data obtained during nine separate one-day surveys of the same zone were processed.

During each expedition, measurements were organized along 3–5 shore-normal profiles of 1.5 to 4 km in length (depending on the observed size of the river plume), usually from the 5-m isobath to the 30-, 40-, or 50-m isobath, with interprofile intervals of 1–3 km. Continuous observations of the surface-layer parameters were performed during the movement of the vessel

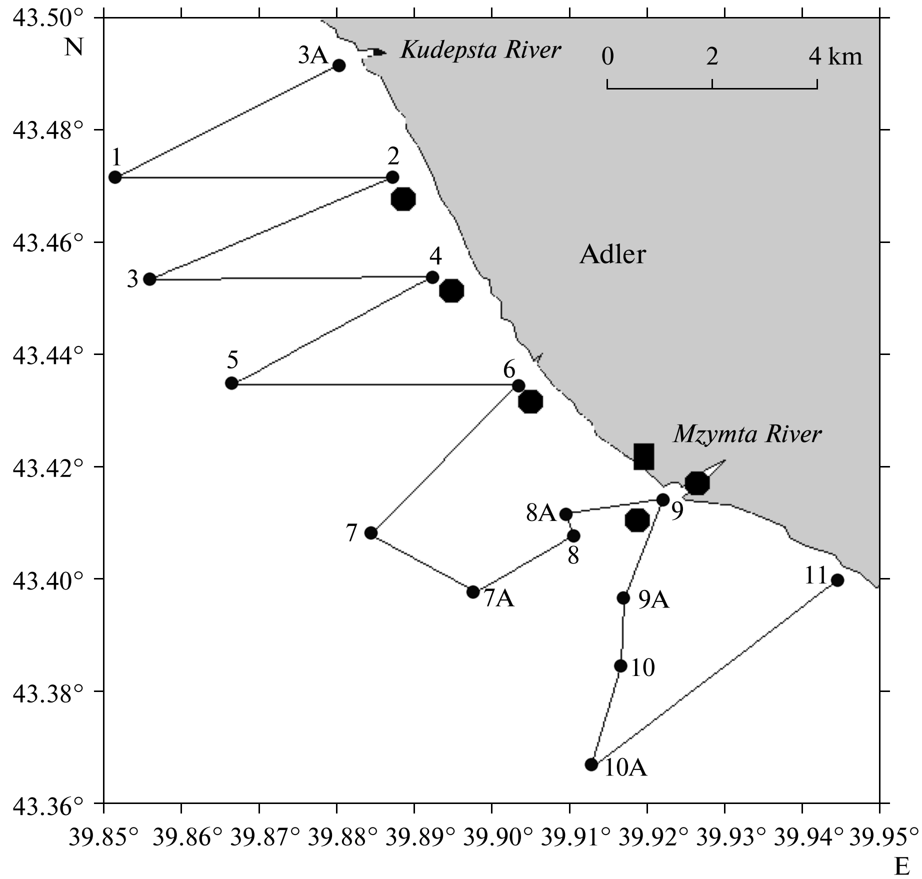

Fig. 1. Organization of measurements in the Mzymta–Kudepsta area: (solid line) vessel trajectory; (points) hydrological stations; (large circles) anchored stations with flowmeters; (square) portable meteorological station.

along and between the profiles. An example of profile locations in the zone under study is given in Fig. 1.

The following measuring equipment was used:

(1) A flow-through sounding system consisting of a centrifugal pump feeding seawater at a rate of about 1 L/s installed in a special container of 30 L on the deck of an SBE911 or SBE19plus CTD probe. The data were then averaged over 10-s intervals.

(2) A UFL-8 or UFL-9 ultraviolet fluorescence lidar installed on the forecast foredeck of a boat or a vessel, which provided rapid underway determination of the TSS concentration at a frequency of 4 Hz. The specifications of the lidar and the methods of calculating concentration from optical data were reported earlier [1].

(3) An Aquadopp or SeaHorse flowmeter was installed at a depth of 1.5–2.5 m in the Mzymta River bed at 50–100 m from the mouth. The instrument recorded flow velocity values averaged over 10-min intervals for assessing water flow velocity at the moment of river entry to the sea.

(4) A portable automatic HeavyWeather meteorological station was installed on the shore at a height of 8 m above the water level near the river mouth, on an open space far from relief elevations, high trees, and buildings. Wind velocity and direction values averaged over 10-min intervals, as well as all main meteorological elements, were recorded throughout the entire period of observations.

The organization of work in the zone was described in more detail earlier [3], as well as the characteristics of the ultraviolet fluorescence lidar [1, 5] and the application of a flow-through measuring system [2].

CALCULATION PROCEDURE

This method involves the joint analysis of data on salinity and TSS concentration at the sea surface. Given the background salinity of the seawater far from the river mouth and the river water salinity in the estuary, the relative content of river runoff in any point of the offshore strip can be unambiguously determined from the water salinity at this point. If the allochthonous suspension was not deposited but only redistributed during the mixing of sea and river water, its concentration would also be completely determined from the relative content of river runoff in the sea water and could be calculated from the actual salinity, the initial TSS concentration in the river estuary, and the background TSS concentration in the sea water far from the river mouth. In practice, observed concentration of TSS is usually lower than the values obtained by this method (except the separate points mainly located in shallow waters and excluded from our consideration), which we attribute to the partial TSS loss due to deposition. Thus, the deposition value can be estimated as the difference between the TSS concentration determined from the mixing of sea and river water masses and the observed concentration.

Equations can be easily derived for the calculation of deposition and mixing values of TSS in accordance with the above logical scheme.

Let P be the content of TSS (g/m^3) settled from the studied water element during the period between the exit of water from the estuary and the measurement moment; M is the content of TSS (g/m^3) left this element because of turbulent mixing with the surrounding sea water; $C_{\max}$ and $C_{\min}$ denote the concentration of TSS (g/m^3) in the river estuary and in the sea beyond the zone affected by the river runoff, respectively; $S_{\max}$ and $S_{\min}$ denote the salinity in the sea beyond the zone affected by the river runoff and in the river estuary, respectively; and C_{obs} and S_{obs} are the current values of TSS concentration and salinity at the specific point of the area, where the values of P and M are to be calculated. We consider a unit volume of water in the studied point and state that this water results from the mixing of some volume v of river water with salinity $S_{\min}$ and the volume $(1 - v)$ of marine water with salinity $S_{\max}$. Thus it follows from the condition of conservation of the total salt mass that

$$vS_{\min} + (1 - v)S_{\max} = S_{\text{obs}}, \tag{1}$$

then,

$$v = (S_{\max} - S_{\text{obs}})/(S_{\max} - S_{\min}). \tag{2}$$

Thus we know the relative volumetric contents of river and background seawater in the studied water volume. A balance equation analogous to Eq. (1) may be written as follows:

$$v(C_{\max} - P/2) + (1 - v)C_{\min} = C_{\text{mix}}, \tag{3}$$

where C_{mix} is the TSS concentration that should result from the mixing of river and sea water. The first term in Eq. (3) needs explanation. In contrast to the salinity, which varies only due to mixing, the TSS concentration decreases due to both mixing and settling. Therefore, during the period between the exit of the water element from the estuary and the observation moment, the sea water is mixed with river water that did not have the initial concentration $C_{\max}$ but a lower "effective" concentration in a range from $(C_{\max} - P)$ at the observation point to $C_{\max}$ at the estuary. Under the simplifying supposition that the deposition of TSS from every liquid particle occurred with a constant rate, we may take the TSS concentration in the river water (averaged over the mixing period) to be equal to $C_{\max} - P/2$, as in Eq. (3).

By definition, $C_{\text{mix}} = C_{\text{obs}} + P$. Substituting this in Eq. (3), we obtain an equation for P. Also by definition, $M = C_{\max} - C_{\text{mix}}$. After simple transformations, we obtain the final equations

$$P = 2[v(C_{\max} - C_{\min}) + C_{\min} - C_{\text{obs}}]/(2 + v), \tag{4}$$

and

$$M = C_{\max} - v(C_{\max} - P/2) - (1 - v)C_{\min}, \tag{5}$$

where v is determined from Eq. (2).

Thus, to assess the accumulated deposition of allochthonous suspension for every liquid particle, it is sufficient to measure only the total TSS concentration and salinity in the target point and to determine their reference values directly at the river estuary and far from it. For the practical implementation of this scheme in the present work, the data of the lidar and the flow-through measuring system were interpolated at the nodes of the regular grid with 100-m intervals; the contents of the deposited and mixed suspensions were then calculated for each node using Eqs. (4)–(5).

RESULTS AND DISCUSSION

From the materials of the three expeditions, data from nine one-day surveys with simultaneous measurements of salinity and TSS concentration were selected (May 27–30 of 2010, May 28–31 of 2011, and May 16 of 2012).

The distributions of settled suspension and suspension lost due to turbulent mixing (averaged over 9 days) in the studied area are shown in Fig. 2. The following features of these distributions may be noted.

The spatial distribution patterns of the deposited and mixed suspensions are almost similar, although the absolute content of the mixed suspension exceeds that of the deposited suspension in most of the grid nodes by about 2 times within the plume area and by 3 times and more beyond the plume. The zones of the most intensive deposition and mixing are localized to the south and southeast of the river mouth, where the river plume was most frequently observed in the sampling days.

It is also interesting that the maximum values of suspension deposition and loss due to mixing are observed at about 1 km from the river mouth rather than directly at the estuary, where the TSS concentration is maximum. It may be supposed that at shorter distances from the estuary, river flow into the sea still retains high velocity due to inertia and traverses this area within too short of a time for the deposition and mixing of the major part of suspension.

The relationship between TSS deposition and the distance from the river estuary averaged over 9 days is shown in Fig. 3. In this function, it is reasonable to express the distance in fractions of the inertia radius $R_{\text{in}} = U/f$ (where U is the initial velocity of the particle in the estuary, and f is the Coriolis parameter) rather than in absolute units. The fact is that the absolute horizontal dimensions of the suspension-carrying river plume significantly depend on runoff velocity

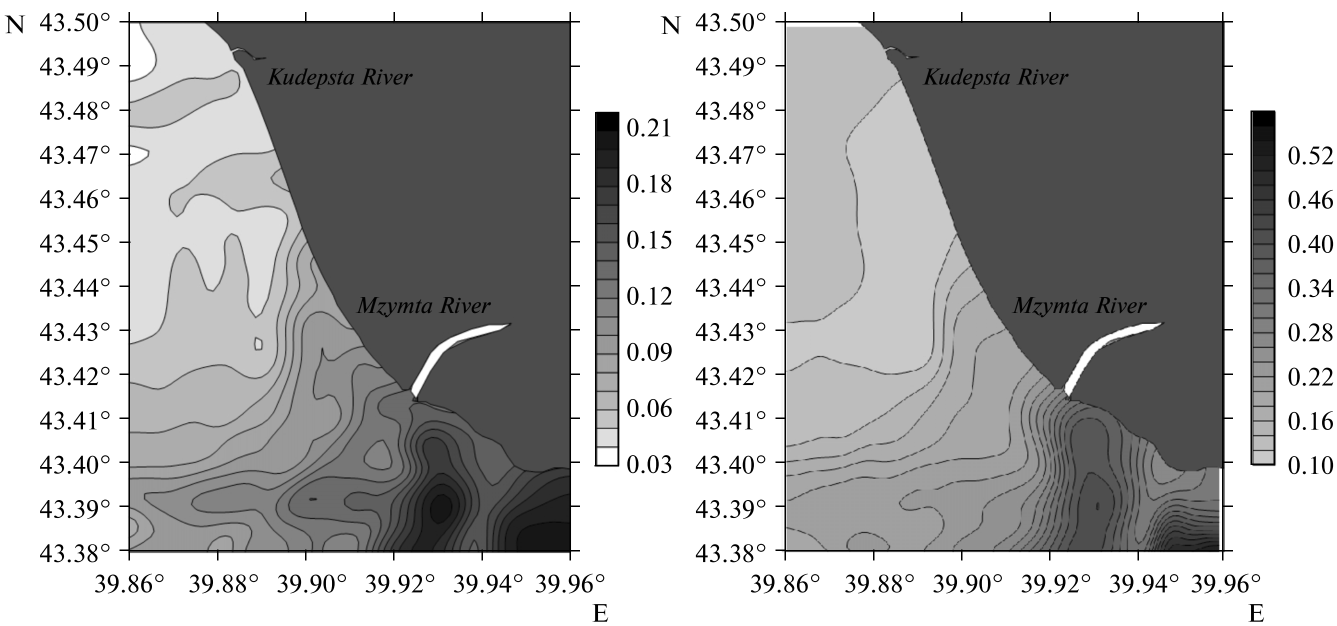

Fig. 2. Spatial distribution of allochthonous suspension removed from river water spreading in the sea due to deposition (left) and mixing (right), % of initial TSS concentration in estuary (averaged over 9 days).

under specific conditions, while the values scaled to the inertia radius give a more unified look to the internal plume structure. Inertia radius values vary in time depending on the river runoff rate; they can be estimated from the data of a flowmeter installed directly in the river estuary, as was done for each measurement day. An average (over the spatial coordinates) value of deposition was calculated using Eq. (4) for the grid points within the area limited by the circles with radii equal to $0.1R_{\text{in}}$ and $0.2R_{\text{in}}$, $0.2R_{\text{in}}$ and $0.3R_{\text{in}}$, ..., and $0.9R_{\text{in}}$ and R_{in}. These values were then averaged over the all 9 days, and the curve presented in Fig. 3 was thus plotted.

This procedure involves a significant averaging over space and time; therefore, a smoothed relationship is obtained, and the variability of suspension deposition determined from it is low in absolute value compared to actual observations. However, it can be seen that the highest deposition values are observed at short distances from the estuary (about $0.3R_{\text{in}}$). There is a local maximum in this region, which agrees with what was stated above in the discussion on Fig. 1 (although this maximum is small, and its significance can be put into question). As the distance from the estuary increases further, deposition decreases, first slowly and then abruptly.

Finally, Fig. 4 shows the content of TSS deposited within the circular area with the center in the river estuary limited by the inertia radius as a function of wind friction stress τ. The latter was calculated from the measured wind velocity using the equation

$$\tau = \rho_a C_D V_{10}^2, \qquad (6)$$

where ρ_a is the air density; V_{10} is the wind velocity at a height of 10 m; and C_D is the roughness coefficient [6]. Wind-friction stress averaged for the corresponding day was determined. The day of May 28, 2011, which was characterized by the passage of an atmospheric front and high wind variability, was excluded from the consideration.

In spite of the relatively large spread of points, a rather unexpected conclusion can be drawn from data in Fig. 4: according to our measurements and calculations, the deposition rate of the suspension generally increased with the wind velocity for the days of obser-

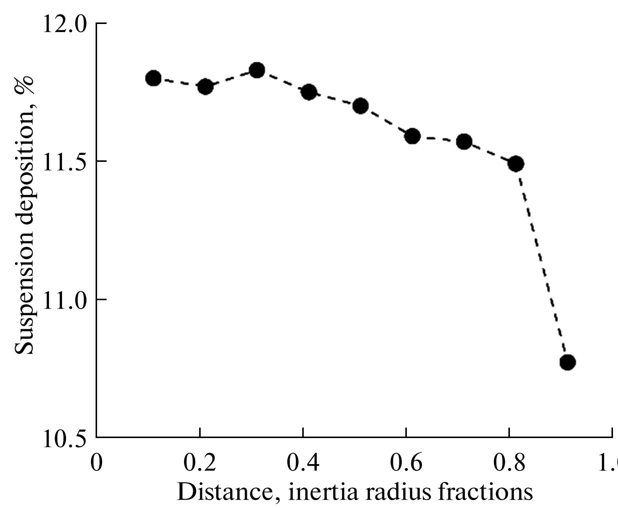

Fig. 3. Content of deposited river sediments (% of the initial TSS concentration) as a function of distance from estuary scaled to inertia radius.

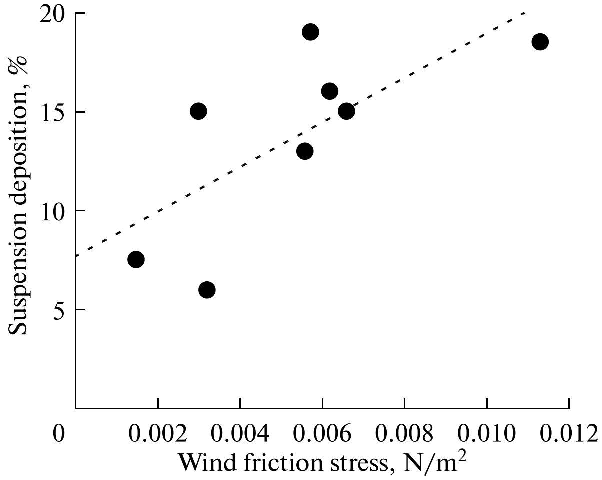

Fig. 4. Content of river sediments (% of the initial TSS concentration) deposited within the circle of the inertia radius with center in the river estuary as a function of wind friction stress (wind velocities used are averaged over current day).

vations. The linear correlation with the determination coefficient $R^2 = 0.51$ is denoted by a dashed line. No similar relationship has been reported earlier. Hypothetically, it can be related to the enhanced coagulation of suspension particles with increasing turbulent exchange in the near-surface layer. This potential mechanism will be an object of further investigations.

CONCLUSIONS

A simple method is proposed for calculating the deposition and mixing of river suspension in the nearshore zone and mapping the deposition rate in near-estuary sea areas. The method involves the joint analysis of the freshwater and suspension balances from the data on the salinity and TSS concentration at the sea surface.

In our opinion, the advantages of this method include its relative technical simplicity and the attainability of high spatial resolution using the almost routine measurements performed on many expeditions of the Institute of Oceanology, Russian Academy of Sciences. A large body of data on the near-estuary areas in the Black, Kara, and South-China seas, as well as the Issyk Kul and Balaton lakes, has been accumulated in recent years and will be probably accumulated in the future. These data can also be used for the above purposes, which will significantly expand the volume of natural information on suspension transport and deposition.

Naturally, the method also has serious limitations. First, it significantly depends on the supposition that fresh-water runoff from a specific river is the only additional source of suspension input into a near-estuary sea area, which is not completely true: the potential advection of suspension from remote sources should generally be taken into consideration, as well as the aeolian removal of material from the land and the resuspension of bottom sediments in shallow areas (the latter factor could be a reason for the negative deposition values obtained from the calculations using Eqs. (4)–(5) for some points near the shore, as was noted above). The proposed method is applicable only to situations when the contribution of the river to the input of suspension into the sea significantly exceeds the contributions of other mechanisms. However, similar situations are frequently realized in the near-estuary areas. The constancy of the deposition rate over time, used in the derivation of Eqs. (4)–(5), is also a simplified concept. Finally, the method can estimate only the integral deposition of suspension and provides no information on changes in particle-size distribution (although this can be considered as an advantage in some respects, because the method needs no expensive particle-size analysis). In our opinion, the proposed method can be a useful tool for studying the deposition and mixing of allochthonous mixtures in the nearshore sea zone.

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