METHOD FOR QUANTIFYING ADVECTION, TURBULENT MIXING, AND GRAVITATIONAL SETTLING OF RIVER-BORNE SUSPENDED SEDIMENTS IN COASTAL AREAS FROM THERMOHALINE AND OPTICAL MEASUREMENTS

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This work presents an original method for quantifying advection and turbulent mixing of river-borne suspended sediments. The main idea of the method consists in joint analysis of surface distributions of salinity and sediment concentration in coastal areas influenced by river discharge. Basing on the Lagrangian approach we represent a river plume as a set of individual water particles, which inflow from a river mouth, mix with ambient sea water during their motion within a river plume and finally dissipate. Surface salinity and sediment concentration of a particle provides information about its turbulent mixing with undelaying ambient sea waters and gravitational settling of its sediments respectively during the period from its origin in the river estuary till the moment of measurement. Using these integrated Lagrangian characteristics calculated for the whole study area we reconstruct advection streamlines within the river plume and ratio between turbulent mixing and gravitational settling of river-borne suspended sediments. This method was applied to coastal areas situated in the north-eastern part of the Black Sea and the western part of the Philippine Sea. High resolution thermohaline and sediment concentration data were collected using a pump-through system equipped by a CTD instrument and a turbidity sensor.

Key words: suspended sediments, gravitational settling, turbulent mixing, river plume, river discharge, coastal sea

I. INTRODUCTION

River discharge of suspended matter substantially influences many physical, geological and chemical processes in the ocean [1, 2, 3]. Qualitative and quantitative assessments of advection, turbulent mixing and gravitational settling of river-borne suspended sediments in coastal areas are essential for many complex scientific and engineering issues including monitoring of water quality, fishery, and construction of artificial coastal structures.

Most of methods used for quantifying transport and settling of sediments are based on in situ measurements, which include analysis of water and ocean floor soil samples collected at certain locations. Generally these methods are laborious, expensive, and are characterized by relatively low spatial resolution, which is defined by amount and density of sampling stations. In particular, these methods encounter substantial difficulties if applied to sediment discharge of small rivers, because coastal areas adjacent to their estuaries are generally characterized by high spatial and temporal variability of sediment concentration. However, total sediment discharge from small rivers is estimated as 40% of the total land-ocean flux of suspended matter [4], while for certain coastal regions contribution of small rivers can be even more significant [5].

This study presents a new method or quantifying advection and turbulent mixing of river-borne suspended sediments. The novelty of this method comes from an original approach based on continuous measurements of salinity and concentration of suspended sediments at the upper layer in contrast to sampling at discrete stations. This method can be effectively used to evaluate delivery and fate of sediment matter discharged from small rivers and watercourses. In the current study this method was applied to the discharge of the Mzymta River situated in the north-eastern part of the Black Sea and the Peinan River located at the south-eastern part of the Taiwan Island.

II. METHOD

The main idea of the method is the following. Concentration of sediments in river plume waters is determined by two processes: turbulent mixing of a river plume with undelaying ambient sea water caused by shear stress and gravitational settling of suspended sediments. Firstly, basing on salinity measurements within the plume we obtain information about intensity of turbulent mixing. Then we reconstruct intensity of gravitational settling of sediments by subtracting the share of sediments removed by turbulent mixing from the difference between initial concentration of suspended sediments in river water and measured concentration in river plume. This work is an extension of the relevant study which was recently presented in [6].

In this work we focus on river plumes formed at narrow shelves where sea depths are much greater than vertical scales of river plumes. Basing on this fact we do not consider bottom resuspension of sediments and, therefore, assume that continental runoff is the only source of suspended sediments, concentration of sediments in ambient sea waters is homogenous and lower than in inflowing river water.

We consider motion of Lagrangian particles of a river plume jointly in two coordinate systems: geographic (latitude and longitude) and *S*-*C* (salinity and suspended sediment concentration) (Fig. 1). Pathway of any Lagrangian particle starts from the river mouth, and its salinity ($S(t)$) and sediment concentration ($C(t)$) at the initial point are equal to the corresponding parameters of river water (S_{rw}, C_{rw}). During its motion a particle is mixing with ambient sea water which causes proportional increase of its salinity as well as decrease of its sediment concentration. Finally, a particle dissipates in the sea, i.e., S and C becomes equal to the corresponding parameters of ambient sea water (S_{sw}, C_{sw}). Therefore trajectory of any particle in *S*-*C* coordinate system is a curve starting from point A^{SC} and ending in point B^{SC} (Fig. 1b). Hereinafter superscripts ^{SC} and ^{G} indicate objects in *S*-*C* and geographic coordinate systems respectively. Salinity and sediment concentration along the particle trajectory are defined by the equations

$$\begin{cases} S(t) = S_{rw} + \int_0^t u_{TM}\big(x(\tau), y(\tau)\big)d\tau\,, \\ C(t) = C_{rw} - \int_0^t w_{TM}\big(x(\tau), y(\tau)\big)d\tau - \int_0^t w_{GS}\big(x(\tau), y(\tau)\big)d\tau\,, \end{cases} \tag{1}$$

where u_{TM} is a velocity of salinity increase caused by turbulent mixing, w_{TM} is a velocity of suspended sediment concentration decrease caused by turbulent mixing, w_{GS} is a velocity of suspended sediment concentration decrease caused by gravitational settling, $x(t)$ and $y(t)$ are coordinates of a particle trajectory.

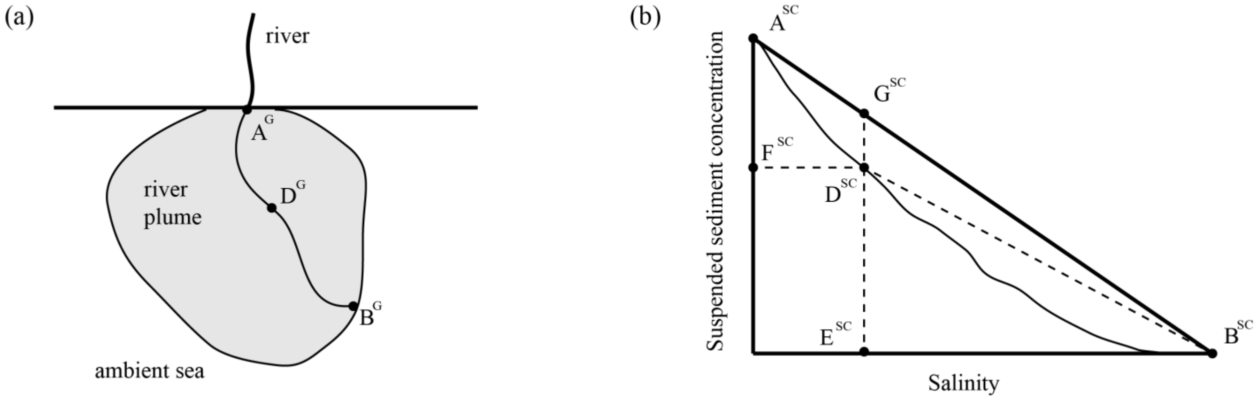

Fig. 1. River plume and a trajectory of its individual particle from its initial inflow from the river mouth till its dissipation in the ambient sea shown in geographic (a) and S-C (b) coordinates.

In case of absence of gravitational settling of particles, i.e., when $\int_0^t w_{GS}\left(x(t), y(t)\right)dt = 0$, both salinity and sediment concentration are determined by u_{TM} and w_{TM} which represent mixing of river plume with ambient sea waters. The trajectory of the particle in *S-C* coordinates coincides with line $A^{SC}B^{SC}$, therefore

$$
\begin{gathered}
\frac{C_{rw} - C(t)}{C_{rw} - C_{sw}} = \frac{S(t) - S_{rw}}{S_{sw} - S_{rw}} \rightarrow \\
\frac{\int_0^t w_{TM}\left(x(\tau), y(\tau)\right)d\tau}{C_{rw} - C_{sw}} = \frac{\int_0^t u_{TM}\left(x(\tau), y(\tau)\right)d\tau}{S_{sw} - S_{rw}} \rightarrow \\
\frac{S_{sw} - S_{rw}}{C_{rw} - C_{sw}} \int_0^t w_{TM}\left(x(\tau), y(\tau)\right)d\tau = \int_0^t u_{TM}\left(x(\tau), y(\tau)\right)d\tau \rightarrow \\
\frac{S_{sw} - S_{rw}}{C_{rw} - C_{sw}} w_{TM}\left(x(t), y(t)\right) = u_{TM}\left(x(t), y(t)\right).
\end{gathered} \tag{2}
$$

Thus, if $w_{GS} = 0$ then according to (1) and (2) sediment concentration depend on salinity as

$$\tilde{C}(t) = C_{rw} - \frac{(S(t) - S_{rw})(C_{rw} - C_{sw})}{S_{sw} - S_{rw}}.$$

If $w_{GS} \neq 0$ then sinking of sediments causes faster decrease of sediment concentration, which results in downward deviation of particle trajectory from the line $A^{SC}B^{SC}$. Moreover, once the particle trajectory reaches point D^{SC} deviated from the line $A^{SC}B^{SC}$ its turbulent mixing with ambient sea continues along the line $D^{SC}B^{SC}$. Therefore for any point D^{SC} of a particle trajectory the segment of the trajectory between point D^{SC} and point B^{SC} is located inside the triangle $D^{SC}B^{SC}E^{SC}$ (Fig. 1b). Basing on the (1) and (2):

$$
\begin{cases}
S(t) = S_{rw} + \dfrac{S_{sw} - S_{rw}}{C_{rw} - C_{sw}} \displaystyle\int_0^t w_{TM}\left(x(\tau), y(\tau)\right)d\tau, \\
C(t) = C_{rw} - \displaystyle\int_0^t w_{TM}\left(x(\tau), y(\tau)\right)d\tau - \int_0^t w_{GS}\left(x(\tau), y(\tau)\right)d\tau
\end{cases} \tag{3}
$$

and

$$C(t) = C_{rw} - \frac{(S(t) - S_{rw})(C_{rw} - C_{sw})}{S_{sw} - S_{rw}} - \int_0^t w_{GS}\big(x(\tau), y(\tau)\big) d\tau = \\ = \tilde{C}(t) - \int_0^t w_{GS}\big(x(\tau), y(\tau)\big) d\tau. \quad (4)$$

Measurements of surface salinity and concentration of suspended sediments within the river plume and ambient sea provide $S(x, y)$, $C(x, y)$ and $\tilde{C}(x, y)$ for any point (x, y) of the study region, thus we can match location of river plume particles in geographic and S-C coordinate systems. If we consider Lagrangian motion of a river particle then $S(t) = S(x(t), y(t)) = S(x, y)$, $C(t) = C(x(t), y(t)) = C(x, y)$, $\tilde{C}(t) = \tilde{C}(x(t), y(t)) = \tilde{C}(x, y)$, where t is the time between origin of the particle at the river mouth and its measurement in the point (x, y). Using (3) and (4) we can reconstruct values of

$$\begin{cases} \int_0^t w_{TM}\big(x(\tau), y(\tau)\big) d\tau = C_{rw} - \tilde{C}\big(x(t), y(t)\big), \\ \int_0^t w_{GS}\big(x(\tau), y(\tau)\big) d\tau = \tilde{C}(x(t), y(t)) - C(x(t), y(t)) \end{cases} \quad (5)$$

for any point (x, y) of the study region. These values represent intensity of gravitational settling of sediments and turbulent mixing within the particle related to its trajectory from the river mouth ($\tau = 0$, point A^{SC}) to the point of measurements ($\tau = t$, point F^{SC}).

In order to reconstruct Eulerian fields of $w_{TM}(x, y)$ and $w_{GS}(x, y)$ from the measured values of $S(x(t), y(t))$ and $C(x(t), y(t))$ we need to differentiate (5):

$$\begin{cases} w_{TM}\big(x(t), y(t)\big) = -\left(\frac{\partial \tilde{C}}{\partial x}\frac{dx}{dt} + \frac{\partial \tilde{C}}{\partial y}\frac{dy}{dt}\right), \\ w_{GS}\big(x(t), y(t)\big) = \left(\frac{\partial \tilde{C}}{\partial x}\frac{dx}{dt} + \frac{\partial \tilde{C}}{\partial y}\frac{dy}{dt}\right) - \left(\frac{\partial C}{\partial x}\frac{dx}{dt} + \frac{\partial C}{\partial y}\frac{dy}{dt}\right) \end{cases}. \quad (6)$$

In order to solve this equation we need to know $\frac{dx}{dt}$ and $\frac{dy}{dt}$, i.e., Eulerian velocity field at the study region.

The ratio $R = \frac{w_{GS}}{w_{TM}}$ is determined by intensity of vertical turbulence ξ_v at the bottom boundary of the river plume, increase of ξ_v causes increase of w_{TM} and decrease of w_{GS} and thus decrease of R. If we assume that R has constant value along the particle trajectory, then according to (3):

$$\begin{cases} S(t) = S_{rw} + \frac{S_{sw} - S_{rw}}{C_{rw} - C_{sw}} \int_0^t w_{TM}\big(x(\tau), y(\tau)\big) d\tau, \\ C(t) = C_{rw} - \int_0^t w_{TM}\big(x(\tau), y(\tau)\big) d\tau - R \int_0^t w_{TM}\big(x(\tau), y(\tau)\big) d\tau = \\ \qquad = C_{rw} - (R + 1) \int_0^t w_{TM}\big(x(\tau), y(\tau)\big) d\tau, \end{cases} \quad (7)$$

therefore for any point D^{SC} within the triangle $A^{SC}B^{SC}O^{SC}$ the only one trajectory between points A^{SC} and D^{SC} with constant R exists, which is defined in the following way:

$$\frac{C_{rw} - C(t)}{R + 1} = \frac{(S(t) - S_{rw})(C_{rw} - C_{sw})}{S_{sw} - S_{rw}} \rightarrow$$
$$R = \frac{(S_{sw} - S_{rw})(C_{rw} - C(t))}{(S(t) - S_{rw})(C_{rw} - C_{sw})} - 1. \quad (8)$$

Thus under the assumption of constant value of R along the particle trajectory for any point (x, y) of the study region we can calculate R using (8) and reconstruct the particle trajectory in S-C coordinate system defined by the equation:

$$\frac{C_{rw} - C(t)}{S(t) - S_{rw}} = \frac{(R + 1)(C_{rw} - C_{sw})}{S_{sw} - S_{rw}} = const. \quad (9)$$

The assumption of constant value of R along the particle trajectory can be used under certain conditions; however, river plumes are generally characterized by substantial variability of ξ_v. In particular, intense mixing in the jet-like near-field plume caused by inertia of plume water dramatically decreases at geostrophic or wind-dominated far-field plume, which results in significant variability of ξ_v and R during particle motion. Trajectories $A^{SC}G^{SC}D^{SC}$ and $A^{SC}F^{SC}D^{SC}$ which are combinations of the extreme cases of $R = 0$, i.e., zero turbulent mixing, to $R = \infty$, i.e., zero gravitational settling, represent minimal and maximal possible values of $\int_0^t w_{GS}\big(x(\tau), y(\tau)\big)d\tau$ for the considered point D^{SC} (Fig. 1b). In the first case suspended sediments in the plume particle were removed only by turbulent mixing (line $A^{SC}G^{SC}$) till the considered moment, characterized by active sinking of sediments (line $G^{SC}D^{SC}$), thus $\int_0^t w_{GS}\big(x(\tau), y(\tau)\big)d\tau$ is equal to minimal possible value. The opposite situation of maximal possible value of $\int_0^t w_{GS}\big(x(\tau), y(\tau)\big)d\tau$ is represented by lines $A^{SC}F^{SC}$ (sinking of sediments in the initial moment) and $F^{SC}D^{SC}$ (subsequent turbulent mixing without gravitational settling). All other possible trajectories of the considered plume particle in the S-C coordinate system are located inside the polygon $A^{SC}G^{SC}D^{SC}F^{SC}$.

Thus, using measured Eulerian fields of $S(x, y)$ and $C(x, y)$ we can estimate only ranges for values of $\int_0^t w_{GS}\big(x(\tau), y(\tau)\big)d\tau$ and $\int_0^t w_{TM}\big(x(\tau), y(\tau)\big)d\tau$, but not their exact values. Moreover, the closer is $S(x, y)$ to S_{sw} the wider is this range, so the considered volumes of sediments can be determined with high accuracy only for a relatively small part of a plume directly adjacent to river mouth. Therefore more accurate estimation of $\int_0^t w_{GS}\big(x(\tau), y(\tau)\big)d\tau$ and $\int_0^t w_{TM}\big(x(\tau), y(\tau)\big)d\tau$ for the whole considered area requires additional data about trajectories of plume particles. We can obtain this information by considering particle motion in its small local vicinity in the following way.

Basing on temporal continuity of salinity and sediment concentration fields we assume that river plume is quasi-stationary on a certain short-term time scale, i.e., its Lagrangian particles move, but its Eulerian distributions of $S(x, y)$ and $C(x, y)$ vary slowly and can be considered as constant during certain short time period Δt. In this case any Lagrangian particle K during this period is transformed into one of the particles of its local vicinity of radius $r = v_{max} \Delta t$, where v_{max} is the maximal possible value of a particle velocity. We consider this small vicinity L^G of the particle K^G in geographical coordinates and represent its image L^{SC} in S-C coordinates (Fig. 2). Therefore, the whole trajectory of the particle $K(\tau)$ during the period $[t - \Delta t/2,\ t + \Delta t/2]$ represented in S-C coordinates coincides with some trajectory in L^{SC} which represents state of L^G at the moment $\tau = t$.

As it was discussed above ξ_v is not homogenous within the whole river plume, however, basing on spatial continuity of vertical turbulence field we can assume that ξ_v is homogenous in some small local vicinity of the considered point K, therefore R is constant for trajectories of all particles within this local vicinity L^G. According to (6):

$$R = \frac{w_{GS}(x(t), y(t))}{w_{TM}(x(t), y(t))} = \frac{\frac{\partial C}{\partial x}\frac{dx}{dt} + \frac{\partial C}{\partial y}\frac{dy}{dt}}{\frac{\partial \tilde{C}}{\partial x}\frac{dx}{dt} + \frac{\partial \tilde{C}}{\partial y}\frac{dy}{dt}} - 1 = \frac{\frac{\partial C}{\partial x}\left(\frac{dx}{dt}\Big/\frac{dy}{dt}\right) + \frac{\partial C}{\partial y}}{\frac{\partial \tilde{C}}{\partial x}\left(\frac{dx}{dt}\Big/\frac{dy}{dt}\right) + \frac{\partial \tilde{C}}{\partial y}} - 1. \tag{10}$$

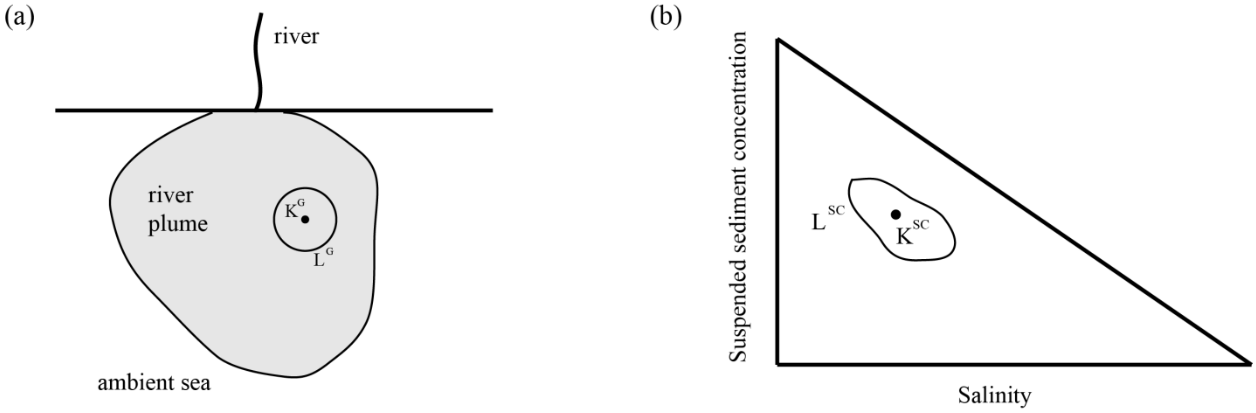

Fig. 2. Small vicinity of a river plume particle in geographic (a) and S-C (b) coordinates.

If we also assume that $\frac{dx}{dt}\Big/\frac{dy}{dt} = T$ is constant in L^{SC}, i.e., velocity direction is constant for all particles in L^G then

$$R = \frac{T\frac{\partial C}{\partial x} + \frac{\partial C}{\partial y}}{T\frac{\partial \tilde{C}}{\partial x} + \frac{\partial \tilde{C}}{\partial y}} - 1. \tag{11}$$

We vary value of T from $-\infty$ to $+\infty$ for all points (x, y) of L^G and calculate the respecting values of $R(x, y)$ using the (11). If the obtained range of values of $R(x, y)$ is large for the points of L^G then the selected radius r is too big to assume homogeneousness of distributions of S, C and ξ_v within L. In this case we decrease r till the range of values of $R(x, y)$ will be small, i.e., parallel particle trajectories in L^G (due to assumption of constant velocity direction) will correspond to "parallel" (with the same value of R) particle trajectories in L^{SM} (due to assumption of constant vertical turbulence).

Once we obtained value of T, we reconstruct local trajectory of point K and calculate $R = \frac{w_{GS}(x(t),y(t))}{w_{TM}(x(t),y(t))}$. Calculating local trajectories for all points of the area influenced by river plume we can reconstruct streamlines within the river plume. The obtained distribution of R can be regarded as relative distribution of $1/\xi_v$. However, we do not know Eulerian velocity field within the river plume, therefore we require additional data to reconstruct absolute values of $w_{GS}(x, y)$ and $w_{TM}(x, y)$. In particular, it is possible if surface measurements of salinity and sediment concentrations are accompanied by high frequency radar sensing which provides data of speed and direction of surface currents, which will be addressed in our future research.

III. RESULTS AND DISCUSSION

In this study the method described above was applied for quantifying advection and turbulent mixing of river-borne suspended sediments discharged from the Mzymta River situated in the north-eastern part of the Black Sea and the Peinan River located at the south-eastern part of the Taiwan Island. Salinity and turbidity data were collected during three field surveys conducted on 16 April 2014 and 16 November 2015 at the Philippine Sea coastal area adjacent to the Peinan River mouth and on 27 May 2015 at the Black Sea coastal area adjacent to the Mzymta River mouth.

The presented method requires high spatial resolution data of salinity and concentration of suspended matter in the concerned region which is able to resolve areas of homogenous Eulerian fields (S, C, ξ_v), i.e., small vicinities of plume particles described above. Due to this reason the in situ data was collected by a pump-through CTD system equipped with YSI-6600V2 instrument with YSI 6136 turbidity sensor. Measurements by a pump-through system were performed at the upper sea layer along the ship track and their spatial resolution was about 25 m. The resulting surface salinity and turbidity distributions at the study regions are shown on Fig. 3-5.

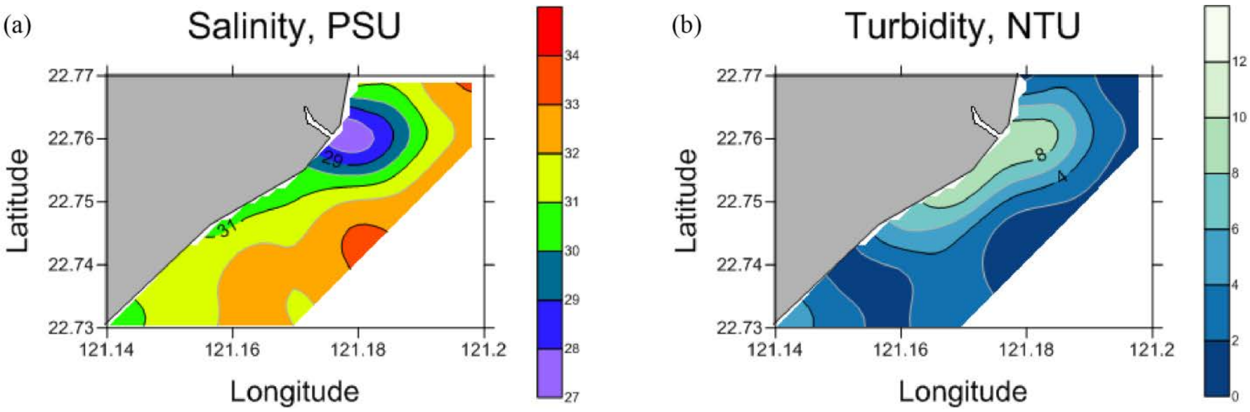

Fig. 3. Distributions of surface salinity (a) and turbidity (b) on 16 April 2014 at the Philippine Sea coastal area adjacent to the Peinan River mouth.

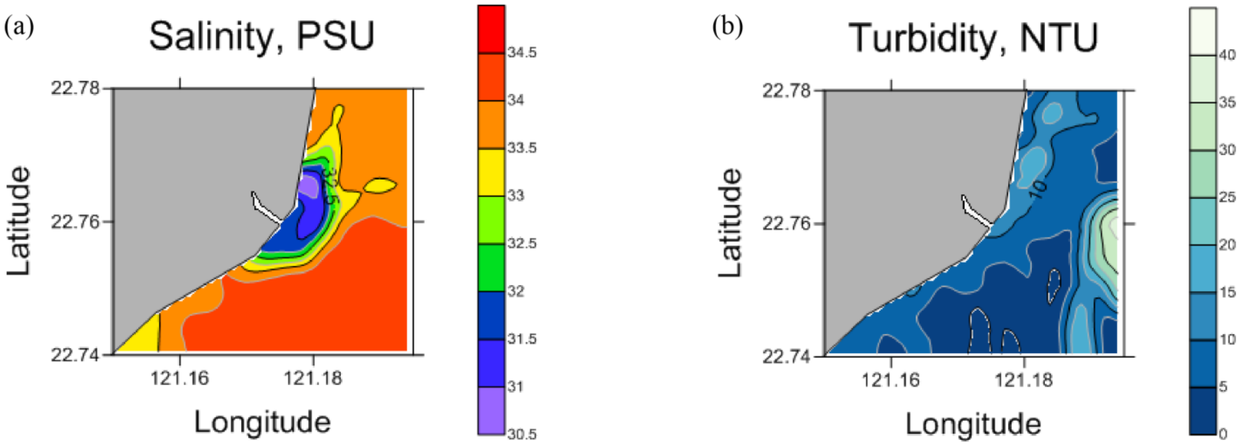

Fig. 4. Distributions of surface salinity (a) and turbidity (b) on 16 November 2015 at the Philippine Sea coastal area adjacent to the Peinan River mouth.

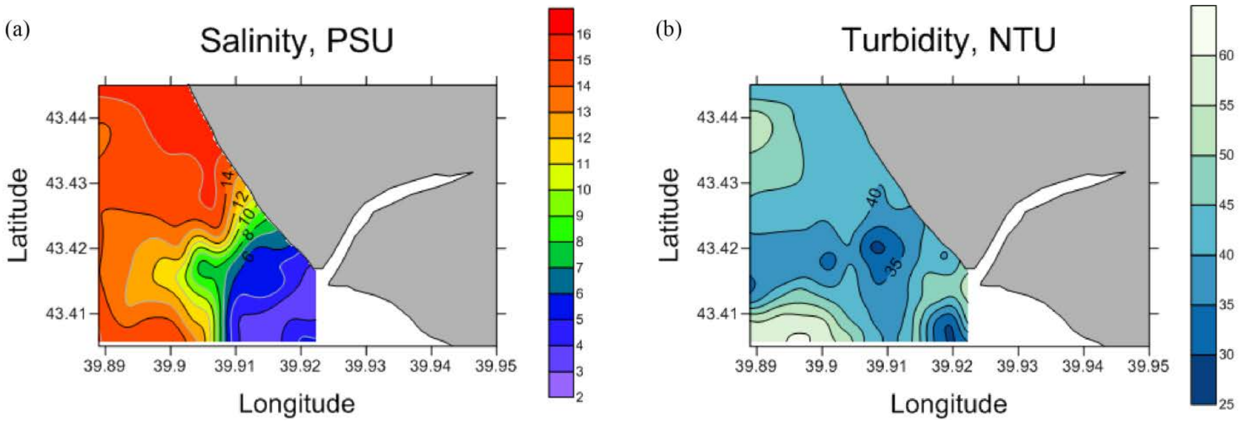

Fig. 5. Distributions of surface salinity (a) and turbidity (b) on 27 May 2015 at the Black Sea coastal area adjacent to the Mzymta River mouth.

Basing on the collected salinity and turbidity data we applied the described method to the coastal areas at the study regions and reconstructed streamlines and distributions of parameter *R*, which is inversely proportional to vertical turbulence ξ_v within the Mzymta and Peinan river plumes (Fig. 6-8). The obtained streamlines shows that the Peinan plume on 16 April 2014 had a typical morphology with a recirculating bulge and an alongshore current formed under low external forcing conditions, while spreading of the Mzymta plume on 27 May 2015 and the Peinan plume on 16 November 2015 were governed by moderate northern winds.

The obtained distributions of parameter *R* shows that both study regions are characterized by reduced values of *R* at near-field parts of the plumes, i.e., plume region adjacent to the river mouth where influence of initial river inflow momentum on plume dynamics dominates over influence of buoyancy. This effect is caused by flow instabilities in a stratified sea generated by a shear stress, therefore ξ_v exhibit maximum near the river mouth and decreases offshore due to deceleration of a plume speed [7, 8, 9]. Secondly, distributions of *R* are low at the plume fronts due to increased vertical turbulence which is also consistent with previous studies of mixing within river plumes [10, 11].

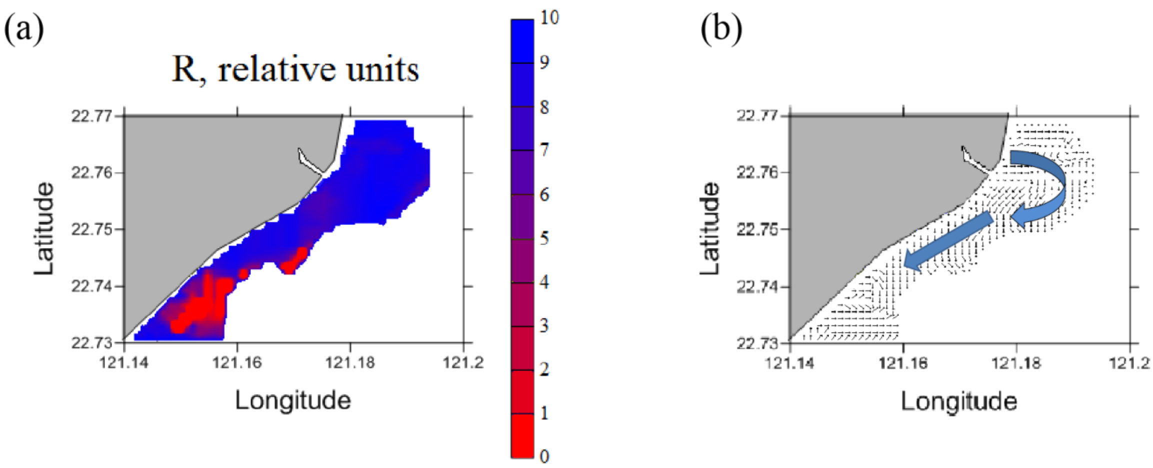

Fig. 6. Distribution of parameter R (a) and general pathways of sediment advection based on distribution of directions of surface currents (b) on 16 April 2014 at the Philippine Sea coastal area adjacent to the Peinan River mouth.

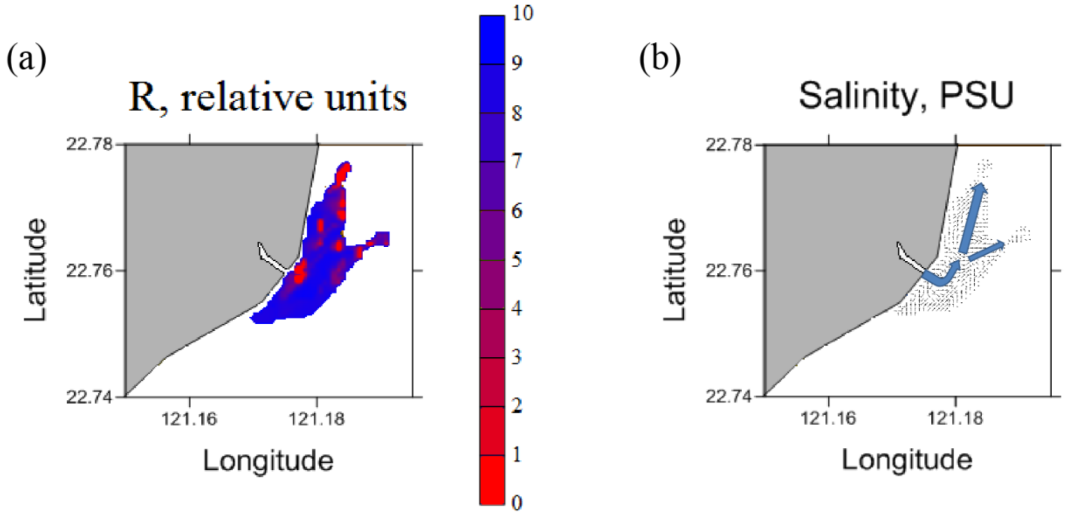

Fig. 7. Distribution of parameter R (a) and general pathways of sediment advection based on distribution of directions of surface currents (b) on 16 November 2015 at the Philippine Sea coastal area adjacent to the Peinan River mouth.

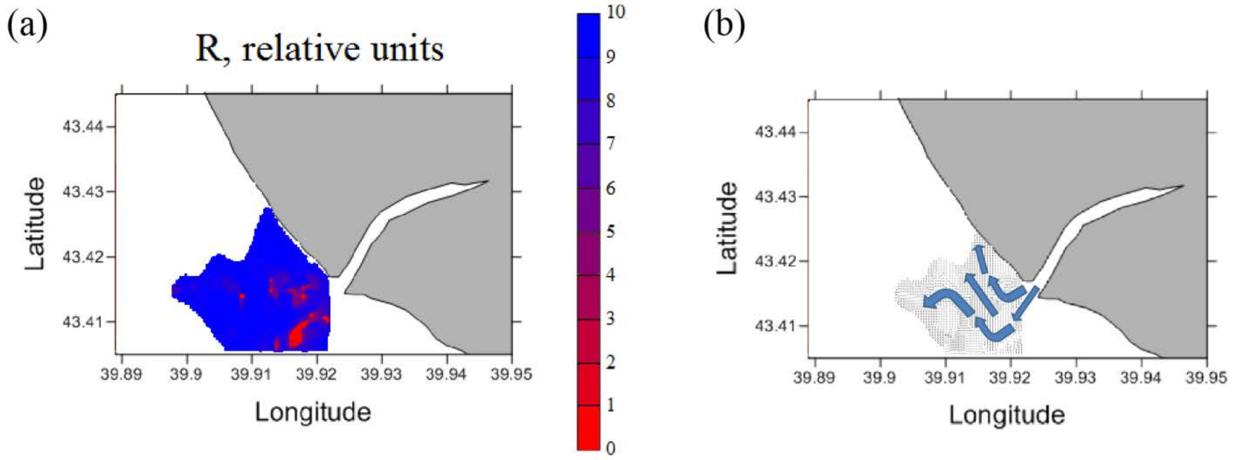

Fig. 8. Distribution of parameter R (a) and general pathways of sediment advection based on distribution of directions of surface currents (b) on 27 May 2015 at the Black Sea coastal area adjacent to the Mzymta River mouth.

IV. CONCLUSIONS

We developed an original method of evaluating advection and turbulent mixing of river-borne suspended sediments in the coastal areas influenced by river discharge. This method is based on high resolution data of distributions of salinity and concentration of suspended sediments in the upper sea layer. This method was applied to the two coastal regions; the first one is adjacent to the Mzymta River mouth in the north-eastern part of the Black Sea, while the second is situated at the western part of the Philippine Sea at the south-eastern part of the Taiwan Island and is adjacent to the Peinan River mouth. Using the method we reconstructed general pathways of sediment advection within the considered river plumes, as well as identified areas of intense (near-field plume and plume fronts) and reduced (far-field plume) vertical turbulent mixing which governs concentration of suspended sediments in the upper sea layer. The obtained results shows good agreement with previous works focused on transport and mixing processes in river plumes [12], thus the developed method is applicable for quantifying advection and turbulent mixing of suspended sediments at buoyant plumes with spatial and temporal scales similar to the plumes of the Mzymta and Peinan rivers.

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