Indian Journal of Geo Marine Sciences
Vol. 52 (02), February 2023, pp. 53-64
DOI: 10.56042/ijms.v52i02.6929

Modeling of accumulation areas of cohesive sediments entering the southeastern Black Sea from Degirmendere River

Devran Yazir*

Karadeniz Technical University, Faculty of Marine Sciences, Department of Maritime Transportation and Management Engineering, 61600, Trabzon, Türkiye

*[E-mail: dyazir@ktu.edu.tr]

Received 17 January 2023; revised 28 January 2023

Modeling transport, accumulation, and deposition areas of sediments are essential for assessing risks to coastal areas and the environment. In this study, the advection-dispersion and accumulation areas of cohesive sediments entering the Black Sea from Degirmendere Basin, the largest river basin on the Southeastern Black Sea coast, were modeled using the POMSED module, which is a submodule of The Princeton Ocean Model (POM). The fate of cohesive sediments in the marine environment has been predicted by different parameters, such as the change in the amount of cohesive sediment entering the Southeastern Black Sea, the dominant surface circulation, the effect of the wind pattern, and the anticyclonic cycle. In the high-flow seasons, the sediment drift velocity is also high. For large sediment drift velocity, cohesive sediments accumulate heavily in coastal areas east of the study area. It has been determined that high sediment drift velocity is the most influential parameter in determining the accumulation areas of cohesive sediments. In the low-flow seasons, the sediment drift velocity is also small. For small sediment drift velocity, cohesive sediments accumulate at the river's mouth under the influence of the predominant wind. This study will constitute the basis for coastal interventions to be carried out in the Southeastern Black Sea, port cleaning study plans, and risk assessment studies for areas where fishermen's shelters are located.

[**Keywords**: Cohesive sediment, Dominant surface circulation, Sediment drift velocity, Sigma-coordinate system, Wind pattern]

Introduction

Movement and transport of sediment occur in different properties for each hydraulic condition. The transport of sediments is constantly changing from the beginning of the river to the end[1]. It is challenging to model the movement and transport of sediment in rivers, but also it is even more challenging to model its behavior in the marine environment after reaching the sea. River discharges are the primary and most important determinant of many hydrological and morphological features of estuaries, deltas, semi-closed coastal water bodies, and open coastal regions[2,3]. In the Southeastern Black Sea region, the parts of the sediments reaching the sea accumulate in the coastal areas with the effect of the dominant surface circulation and wind pattern, while some of them remain in resuspension in the marine environment. The gyre is the predominant surface circulation – a well-organized, roughly circular flow. In the Southeastern Black Sea region, soil erosion occurs intensively because of the rugged terrain and continuous rainfall[4]. As a result of intense soil erosion, cohesive and non-cohesive sediments and other pollution loads in the marine environment increase[5]. Many factors affect sediment transport physically. One is that sediment transport is closely related to river basin erosion. The Southeastern Black Sea region is a region with high pollution caused by erosion and therefore has coastal areas that are severely degraded[6]. However, interventions associated with anthropogenic natural dynamics have increasingly affected modern coastline systems in the Southeastern Black Sea region. As a result, coastal erosion, and withdrawal lead to a severe increase in coastal sediments.

Breakwaters, jetties, and support walls deployed to prevent coastal erosion disrupt sediment transport and cause severe bottom erosion in the coastal area[2]. Similarly, hydroelectric power plant projects and dams built on rivers have significantly impacted the amount of sediment flowing from rivers to the sea[7]. It has been determined that the effects of large dams built on rivers are generally across the basin. Rivers of the Black Sea, Turkey, are under heavy anthropogenic pressure. Along with these, dozens of large and small dams and reservoirs have been built[2]. Degirmendere Basin, a sub-basin of the Eastern Black Sea Basin, is located within the Trabzon province's borders. It meets the water requirement of Trabzon province with the dam built on Degirmendere. It is also a river with hydroelectric power plants of various sizes constructed across the river region. Degirmendere Basin has fundamental problems such as floods, landslides, erosion, and intense pollution[5,8].

Before the Black Sea coastal road construction, the Degirmendere River was discharging into the Black Sea, approximately 900 meters from the entrance of Trabzon port. However, after completion of the Black Sea coastal road construction, the Degirmendere River has started to discharge into the sea, 150 meters closer to the port than the old point. The choice of the Degirmendere Basin for this study is an area where erosion is very high, and the Trabzon port on the west side of the river's entrance to the sea and fishing shelters on the east side. In the Southeastern Black Sea borders, the dominant wave surface circulation direction is northwest-north, and the general coastline slope is east-west. Also, the direction of net sediment transport is from west to east[4,9]. For this reason, the effects of the cohesive sediments carried by the Degirmendere River to the port entrance and fishermen's shelters in the area where the river discharges into the sea are modeled.

In this study, the fates, that is, advection-dispersion, accumulation, and deposition areas of cohesive sediments in the marine environment entering the Southeastern Black Sea from Degirmendere Basin, has been modeled and analyzed using the POM package program. Since the basin is a region with abundant rainfall, the soil structure is also suitable for sediment transportation. Therefore, the geomorphological structure and soil structure of the Degirmendere Basin causes intense sediment transport to the Southeastern Black Sea. In low-flow seasons, cohesive sediments are generally transported to the southeast Black Sea by the Degirmendere Basin in large quantities. Cohesive sediments have been focused on in this study, as the Trabzon Port located on the west-side of the river entrance and the fishermen's shelters on the eastside are affected by the cohesive sediments carried by the Degirmendere River. By changing the discharge entrance angle of the river-mouth of Degirmendere River into the Southeastern Black Sea, the behavior of cohesive sediments in the marine environment, accumulation, and deposition areas have been examined. Since the seasonal cohesive sediment data entering the sea from the Degirmendere Basin are not up to date, the data applied in this model is based on the data of previous empirical studies. In the model, the amount of cohesive sediment entering the sea for each season, accumulation, and deposition area has been examined separately under the prevailing surface circulation according to different wind directions and intensities. The resuspension and deposition concentration of cohesive sediments at the entrance of Trabzon port has been modeled and analyzed under different parameters. The effects of a fishing port built in the eastern part of Trabzon port on the advection-dispersion, accumulation, and deposition areas of the cohesive sediments entering the sea from Degirmendere have been examined. This study can be a baseline for future field studies, risk assessments, and potential removal activities.

Due to the characteristic natural structure of Degirmendere Basin, flood and landslide potential is high[8]. So, it is very likely that significant disasters will occur if the human factor affects this basin. Therefore, this region's Hydroelectric Power Plant (HEPP) activities should be carried out carefully. Besides, the sediment carried by the floods in the Degirmendere Basin may affect the dam's filling before completing its life, and problems may occur with drinking water. Moreover, it will negatively affect the port area and the turbine wear given to hydroelectric power plants. Hence, it is necessary to investigate how sediments can affect life separately[8]. In a similar article, natural and anthropogenic heavy metal (Cu, Pb, Zn, Ni, and Co) pollution in coastal sediments near Trabzon province was examined spatially and temporally. Metals measured in sediments in Degirmendere, Yanbolu, and Solakli were compared with reference values suitable for sediment quality guidelines[10]. In another paper, the Black Sea coastal region was reported to be threatened by severe coastal erosion due to human damage. For example, it has been said that the sediments accumulated in dams built by humans are influential in determining the characteristics of rivers and the shape of the coastal zone after a while[2]. Hence, estimating sediment load in that coastal area is fundamental in planning, operating, and maintaining water structures in rivers. Therefore, Ozger & Kabatas[1] had tried to solve the sediment load behavior using Wavelet and Fuzzy Logic (WFL) techniques. As a result, it has been stated that the WFL technique had more consistent results than the fuzzy logic approach[1]. The results obtained from these studies generally revealed the amount of cohesive and non-cohesive sediment and pollution carried by Degirmendere to the Southeastern Black Sea.

Further, Fitri *et al.*[3] has investigated sediment transport, erosion and deposition patterns at the separate low-hill breakwater location that protects the cohesive shore of Carey Island, Malaysia with a combined two-dimensional hydrodynamic-sediment transport model based on Reynolds averaged Navier-Stokes equations. Conversely, Droppo & Krishnappan[11] used the RIVFLOC and MOBED models to evaluate the characteristics of cohesive sediment transport in rivers. It has also been found that these two models are instrumental in understanding the flow characteristics of rivers and the behaviors of cohesive sediment dynamics[11]. Spatially varying parameters can be estimated by assimilating suspended sediment concentrations received from the satellite. In a study by Zhang *et al.*[12] have shown that data assimilation and parameter estimation using a combined independent point and Tikhonov regularization scheme can improve the modeling results more effectively. Difficulties in modeling parameters of cohesive sediments prevent the numerical modeling of sediment transport. Therefore, the reference has been made to the three-dimensional combined sediment transport model and its adjoint model by Wang *et al.*[13]. They have simultaneously assimilated data from the Geostationary Ocean Color Imager to four spatially and temporally varying predictions. As a result, they have predicted that the relationships between the estimated parameters and hydrodynamic fields might suggest improving parameterization in cohesive sediment[13]. Sediment types, grain diameters, and transport mechanisms in coastal areas differ. Therefore, different mathematical equations may be needed to model sediment motion[14].

Cohesive sediments are found everywhere in the coastal areas. However, its behavior is complex and, therefore, often oversimplified by computer models. Sherwood *et al.*[15] have explained and demonstrated the algorithms for processing cohesive and mixed sediment added to the Regional Ocean Modeling System. Additionally, the authors simulated important components of cohesive sediment transport. A modified Harten, Lax, and van Leer Riemann solver with the contact wave restored (HLLC) was derived to predict depth-averaged shallow water flow and sediment transport. Samples containing both fixed and movable bearings were tested with the numerical model and as a result, it is understood that the model predictions are generally in good agreement with the measurement[16]. Cohesive sediments play a significant role in shaping the coastal zone and hence, it affects the ecological balance too. In light of this, Vaz *et al.*[17] have investigated the dependence of the water-column light extinction coefficient (k) on cohesive sediment dynamics in the Ria de Aveiro lagoon under sea-level rise and extreme freshwater discharge events and found that the extreme river discharge events exhibit higher impact on water column light penetration than the estimated sea-level rise.

Sediment transport has become a global problem as it causes the deterioration of the ecological balance. Therefore, the model of sediment transport is essential. Information on seasonal sedimentation rates was predicted by Lu *et al.*[18] with a two-dimensional (2D) surface water Flow Model coupled with a Sediment Transport model in the MIKE 21 modeling system. Another study on improving suspended cohesive sediment transport model performance using data assimilation tried to compare the multi-source observations simultaneously to the three-dimensional suspended cohesive sediment transport model in the Bohai Sea with adjoint method[19]. Several studies have been done on critical shear stresses for erosion and sedimentation of cohesive sediments. However, the methods used in the research are not found sufficient. Thus, Feng *et al.*[20] have studied the performance and applicability of five critical erosion shear stress methods derived from different hypotheses on sediment transport. Comparative analysis and validation of existing methods are still lacking. As a result, it will provide an understanding of the mechanisms underlying erosion and cohesive sediment deposition[20]. Another paper analyzed the incipient motion mechanism of the consolidated cohesive precipitate. Also, the differentials affecting the new shear stress were investigated using the previous studies with an experimental device. Verification has also been made with experimental data and theoretical analysis. It is understood that the incipient shear stress values agree with the experimental results[21]. Population Balance Equations are frequently used to analyze better particle sizes in different environmental conditions. Instead of this model, Safar & Chassagne[22] thought that they needed to analyze particles better to stay closer to physical processes, so they proposed an approach based on a logistic growth model that mimics Particle Size Distribution. Zhu *et al.*[23] developed a three-dimensional hydrodynamic and sediment transport model to investigate sediment transport time scales in the China Modaomen Waterway. As a result of the study, it was understood that the fine-grained sediment was transported to the mouth of the river in a shorter time than the coarse-grained sediment. Also, it has been understood that as the transport time of coarse-grained sediments is a long period of time, it will cause deterioration of the water quality and the accumulation of pollutants. In another paper, Orseau *et al.*[24] aimed to better understand and predict hydrodynamic and fine sediment transport within the estuary. That's why they have formulated a two-dimensional hydro-sedimentary model. Tayfur[25] has examined modeling approaches for non-cohesive sediment transport that have been studied for years. As a result, opinions have been made about which methods may be more advantageous in non-cohesive sediment transport, which has been studied experimentally and numerically. Sediments are carried by the forces exerted by waves and currents. Egan *et al.*[26] have conducted a field study to reveal the mechanisms driving cohesive sediment erosion. They also compared these field results with previous studies. As a result, it is said that the findings obtained can be applied to improving sediment transport models. Fine-grained sediment is one reason for rivers' deterioration of water quality. Therefore, extensive knowledge is required for fine sediment. However, the cohesive channel bed sediment's deposition behavior was experimentally studied in a circular channel for improved modeling of fine sediment. The data from the examinations have been used to calibrate and test a mathematical model of flocculation and settling (FLUME)[27]. The results obtained from these studies, on the other hand, are aimed to obtain the most ideal solution by using different mathematical models. While different equations are used to model the cohesive and non-cohesive sediment carried by the river, different equations are used to model the movement of cohesive and non-cohesive sediment in the marine environment. Therefore, different mathematical equations may be needed to model the movement of sediments. On the other hand, Oguz *et al.*[28] studied the Black Sea circulation features based on a basin-scale survey conducted in September-October 1990. For the upper 300-400 dbar, the circulation pattern consists of a cyclonic meandering Edge Current, a limited series of anticyclonic currents between shore and shore. Özsoy & Ünlüata[29] discussed the roles of rising stratification, topography, and coastline changes along the coast in determining the general circulation of the Black Sea Basin and the behavior of fast, unstable boundary currents based on hydrographic data and satellite observations. In addition, the effects of physical processes on the ecosystem are discussed. Stanev[30] stated that since the water and salt balances in the Black Sea are easily controllable and the scales are smaller than in the global ocean, this basin is a useful test site for developing models that can later be applied to larger scales. The primary purpose of the Stanev[30] article is to demonstrate this possibility by using the Black Sea physical oceanography examples based on numerical modeling results. Stanev & Kandilarov[31] stated in their study that the comparison between numerical simulations and remote sensing data adds reliability to the quality of the simulations. The combined effect of wind waves and currents in the bedding layer controls sediment resuspension, which is the primary basin-wide sediment source. As a result, it was concluded that the depositional patterns were related to the specific shape of the Black Sea topography, and the most significant deposits were observed in the continental slope area. Gunduz *et al.*[32] stated in their study that water passages in the Bosporus are of critical importance for the hydrodynamics and hydroclimatology of the Black Sea. It has been noted its vital importance for the hydrodynamics and hydroclimatology of the Black Sea, especially on the Marmara Seaside.

When the literature is reviewed, it has been determined that the modeling methods used in international studies are not used for Degirmendere Basin, one of the largest basins of the Southeastern Black Sea Region. The cohesive sediment and non-cohesive sediment concentration carried by the basin into the sea and the behavior of the transported sediments in the marine environment were generally obtained due to empirical studies. Getting the results of empirical studies for a long time, changes in the basin's structure due to natural and human-induced reasons, and changes in the amount of sediment carried by the basin affect the accuracy of the studies' results. For all these reasons, in this study, the advection-dispersion and accumulation areas in the marine environment of the cohesive sediments transported by the Degirmendere basin to the Southeastern Black Sea are modeled.

Materials and Methods

The movements of the cohesive sediments in the marine environment can be assessed through the results obtained from the numerical models[7,33]. The transportation, advection-dispersion, accumulation, and deposition areas of cohesive sediments released from Degirmendere River in the Southeastern Black Sea have been modeled using The Princeton Ocean Model (POM).

The Princeton Ocean Model (POM)

The Princeton Ocean Model (POM) is used to simulate and forecast oceanic currents, cohesive and non-cohesive sediment transport, particle tracking, temperatures, salinity, and various other water properties. One of the sub-modules of the POM model is the POMSED module which realistically simulates cohesive and non-cohesive sediments across multiple water systems, rivers, lakes, and oceanic and marine coastal waters. The POMSED module uses the same numerical grid and calculation structure as the hydrodynamic model. The POMSED module used in this study simulates the resuspension, transport, and deposition of cohesive and non-cohesive sediments[34-36].

The vertical coordinate system for irregular bathymetric areas

The ordinary (x, y, z) coordinate system has disadvantages in large bathymetric areas. For this reason, a new coordinate system called σ-coordinate system has been described instead of the ordinary (x, y, z) coordinate system, as illustrated in Figure 1. The governing equations are transformed from ordinary coordinates (x, y, z) to (x^*, y^*, σ, t^*)[36-40].

Where, $x^* = x$, $y^* = y$, $\sigma = \frac{z-\eta}{H+\eta}$, $t^* = t$, $D \equiv H + \eta$

By applying the chain rule in the derivative, the following relations are obtained, connecting the derivatives in the old order (x, y, z) coordinate system with those in the new system.

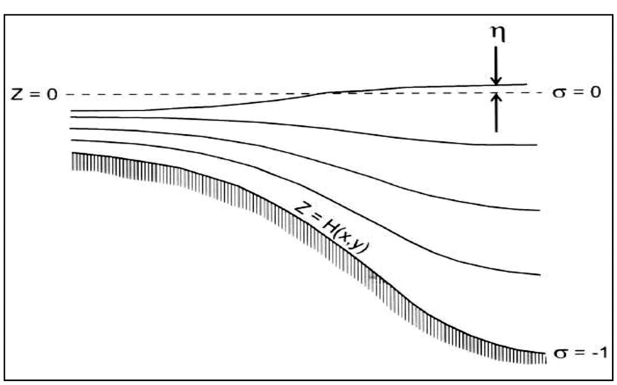

Fig. 1 — σ-coordinate system

$$\frac{\partial G}{\partial x} = \frac{\partial G}{\partial x^*} - \frac{\partial G}{\partial \sigma}\left[\frac{\sigma}{D}\frac{\partial D}{\partial x^*} + \frac{1}{D}\frac{\partial \eta}{\partial x^*}\right] \quad \ldots (1)$$

$$\frac{\partial G}{\partial y} = \frac{\partial G}{\partial y^*} - \frac{\partial G}{\partial \sigma}\left[\frac{\sigma}{D}\frac{\partial D}{\partial y^*} + \frac{1}{D}\frac{\partial \eta}{\partial y^*}\right] \quad \ldots (2)$$

$$\frac{\partial G}{\partial t} = \frac{\partial G}{\partial t^*} - \frac{\partial G}{\partial \sigma}\left[\frac{\sigma}{D}\frac{\partial D}{\partial t^*} + \frac{1}{D}\frac{\partial \eta}{\partial t^*}\right] \quad \ldots (3)$$

$$\frac{\partial G}{\partial z} = \frac{\partial G}{\partial \sigma}\frac{\partial \sigma}{\partial t} = \frac{1}{D}\frac{\partial G}{\partial \sigma} \quad \ldots (4)$$

Where, G is an elective field available, and σ ranges from $\sigma = 0$ at $z = \eta$ to $\sigma = -1$ at z = -H.

A new vertical velocity can be described as[36-40]:

$$\omega \equiv w - U\omega\sigma\frac{\partial D}{\partial x^*} + \frac{\partial \eta}{\partial x^*} - V\sigma\frac{\partial D}{\partial y^*} + \frac{\partial \eta}{\partial y^*} - \left(\sigma\frac{\partial D}{\partial t^*} + \frac{\partial \eta}{\partial t^*}\right) \quad \ldots (5)$$

The boundary conditions,

$$\omega(x^*, y^*, 0, t^*) = 0\,, \omega(x^*, y^*, -1, t^*) = 0 \quad \ldots (6)$$

Governing equation for cohesive and non-cohesive sediment

The three-dimensional advection-dispersion equation for the transport of sediment of size class k (k = 1,2) is:

$$\frac{\partial C_k}{\partial t} + \frac{\partial UC_k}{\partial x} + \frac{\partial VC_k}{\partial y} + \frac{\partial (W - W_{S,k})C_k}{\partial z} = \frac{\partial}{\partial x}\left(A_H\frac{\partial C_k}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial C_k}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_H\frac{\partial C_k}{\partial z}\right) \quad \ldots (7)$$

With the boundary-conditions

$$K_H\frac{\partial C_k}{\partial z} = 0\,, z \to \eta \quad \ldots (8)$$

$$K_H\frac{\partial C_k}{\partial z} = E_k - D_K\,, z \to -H \quad \ldots (9)$$

Where, C_k: is the suspended sediment concentration (k = 1 for cohesive sediment and k = 2 for non-cohesive sediments); u, v, and w: are velocity in the x, y, and z - direction; A_H: is the horizontal diffusivity; K_H: is the vertical eddy diffusivity; E_k, D_K: are the resuspension and the deposition flux; η: is the water surface elevation above a specified datum; and H: is the bathymetric depth below the datum

Resuspension and deposition of cohesive sediments in the marine environment

The quantity of cohesive sediment resuspended from a cohesive sediment bed is given by Gailani *et al.*[41] as:

$$\varepsilon = \frac{a_0}{T_d^m}\left(\frac{\tau_b - \tau_c}{\tau_c}\right)^n \quad \dots (10)$$

Where, ε: is the resuspension intensity (mg cm^{-2}); a_0: is the constant depending upon the bed particulars; T_d: is the time after deposition (days); τ_b: is the bed shear stress (dynes cm^{-2}); τ_c: is the critical shear stress for erosion (dynes cm^{-2}); and m, n: are constants dependent upon the depositional environment in the marine.

The deposition amount for cohesive sediment depends upon the sediment flux approaching the bed and the probability of the flocculation sticking to the bed, according to the formulation of Krone[42] as follows:

$$D_{1} = -W_{s,1} C_1 P_1 \quad \dots (11)$$

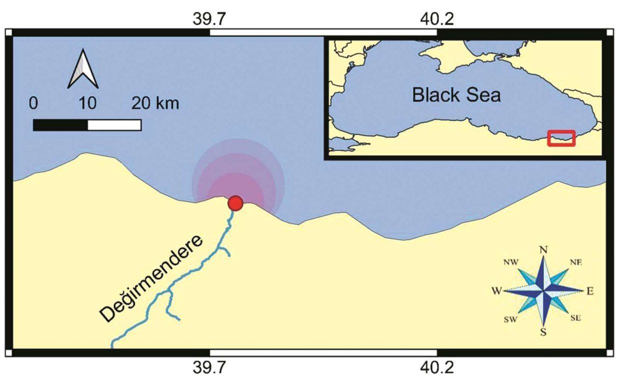

Fig. 2 — Map of the study area and cohesive sediment entrance point

$$P_1 = 1 - \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Y} e^{-\frac{\omega^2}{2}} d\omega \quad \dots (12)$$

$$Y = 2.04 \log\left[0.25\left(\frac{\tau_b}{\tau_{b,min}} - 1\right) e^{1.07\tau_{b,min}}\right] \quad \dots (13)$$

Where, D_1: is the depositional flux (g cm^{-2}s^{-1}); $W_{s,1}$: is the settling velocity of the cohesive sediment flocs (cms^{-1}); C_1: is the cohesive suspended sediment concentration (gcm^{-3}) near the sediment-water interface; P_1: is the probability of deposition; and ω: is the variable of integral.

Study area

Degirmendere River mouth (41°0'9.04" N, 39°45'25.33" E) is chosen as the cohesive sediment entrance point (Figs. 2 & 3) in the present study. Degirmendere Basin, the largest river basin in Trabzon Province, has a total region of 1053 km^2. Most of the basin is located in Macka and Ortahisar (Trabzon Center) districts. It also includes a total of 80 village settlements. Akcaabat and Yomra district's borders and some lands north of Gumushane Province are also within the Degirmendere River basin. The geomorphological features of the basin are essential in terms of rainfall-flow relationships. Since the basin is a region with abundant rainfall, the soil structure is also suitable for sediment transportation. Therefore, the geomorphological structure and soil structure of the Degirmendere Basin cause intense sediment transport to the Southeastern Black Sea[5,8,43]. The study area where the model is applied is hydrodynamically

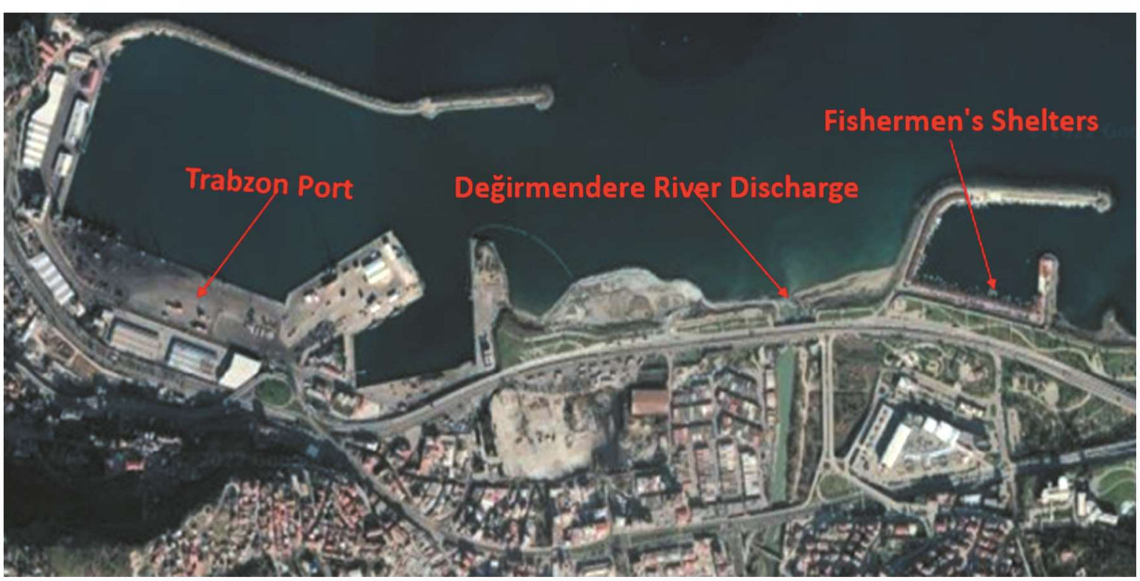

Fig. 3 — View of the study area from Google Maps

under the influence of the central cyclonic cycle of the Black Sea throughout the year and is mainly affected by anticyclonic meandering Rim Current. The Batumi anticyclone, one of the most intense eddy formations, is active in the study area from early March to October[44].

The modeling framework

The fate of cohesive sediments in the marine environment has been studied under different scenarios. Deposition areas in the marine environment of cohesive sediments transported to the Southeastern Black Sea during the high-flow and low-flow seasons were examined separately for different parameters. These parameters include the amount of cohesive sediment entering the Southeastern Black Sea in different seasons, the direction and intensity of the predominant and active winds, the effect of the central cyclonic cycle of the Black Sea, and the effect of the Batumi anticyclone, which is one of the most intense eddy formations. The flow rate of the Degirmendere River is reported as 41.3 m^3/s and 5.1 m^3/s for high-flow and low-flow seasons, respectively[45]. According to the Degirmendere River measurements in 1993, the amount of suspended sediment was 448 mg/l in August, 110 mg/l in May, and 39 mg/l in October. When these values are averaged, the average suspended sediment load of the Degirmendere River can be obtained as 199 mg/l[8]. Current data are challenging to obtain for the concentration of cohesive sediment entering the sea from rivers in the Southeastern Black Sea region. For this reason, cohesive sediment data were applied to the model considering the data presented by Taş[8]. The data for the hydrodynamic module have been retrieved from accessible online sources. Wind data have been recovered from the European Centre for Medium-Range Weather Forecast (ECMWF) (http://www.ecmwf.int). An overall presentation of the average data is given in Figure 4.

Results and Discussion

The advection-dispersion, accumulation, and deposition areas of cohesive sediments entering the Southeastern Black Sea from Degirmendere River have been modeled using the POMSED module in seasons where the sediment drift velocities are high (April) to low (August). The behavior of cohesive sediments in the marine environment has been investigated under different parameters, such as the change in the amount of cohesive sediment entering the sea from Degirmendere River, sediment drift

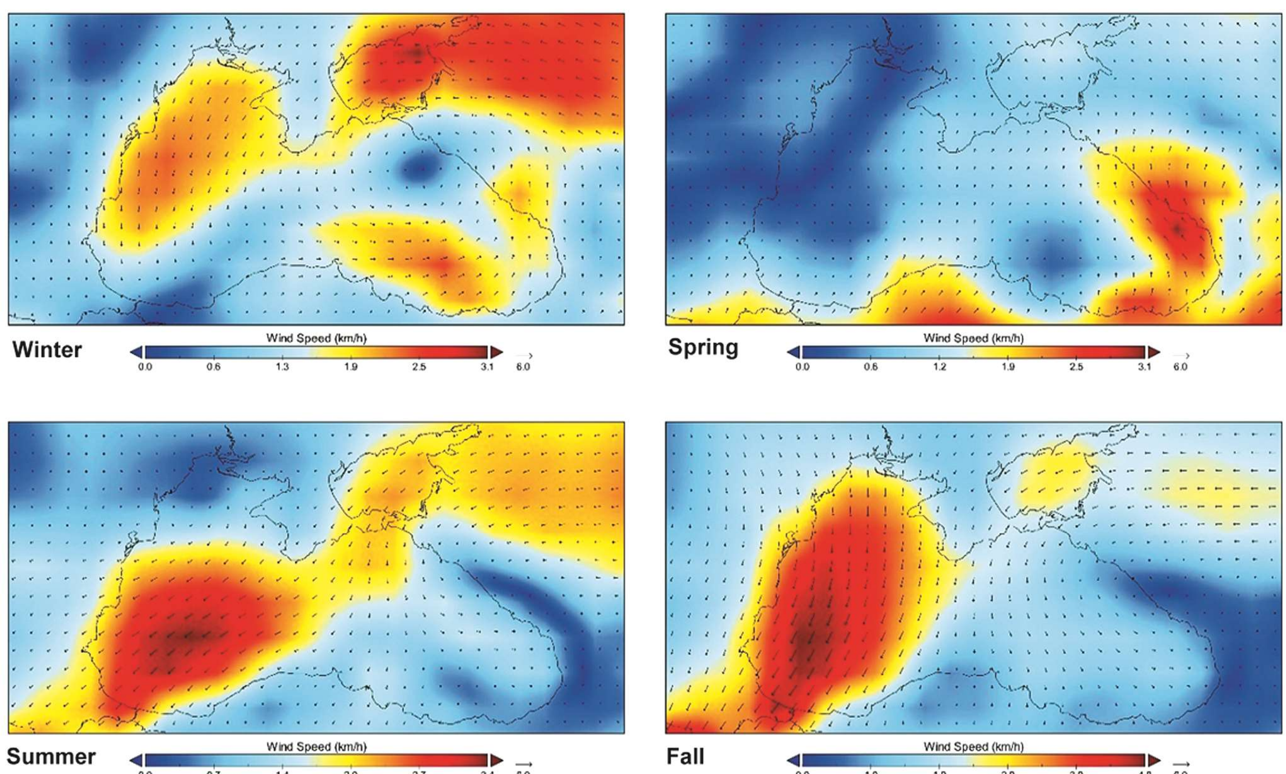

Fig. 4 — Seasonal mean wind direction during high-flow and low-flow seasons

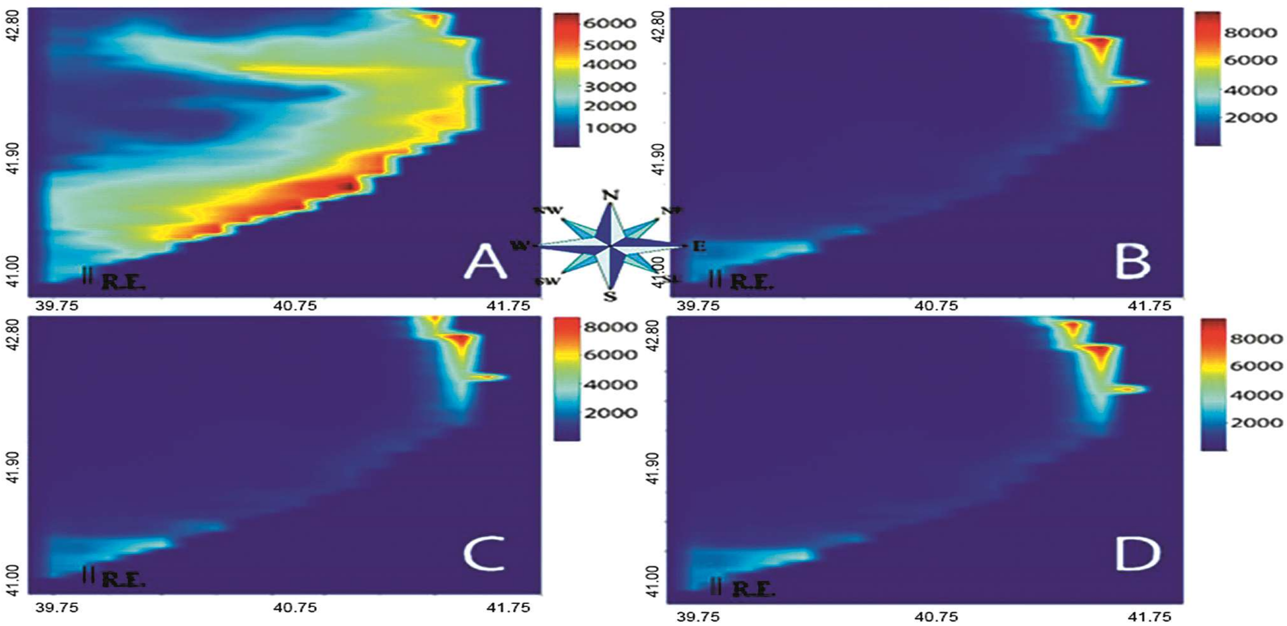

Fig. 5 — Snapshots of cohesive sediment distribution on Southeastern Black Sea for high sediment drift velocity

velocity (river flow velocity), the dominant surface circulation, and the effect of the wind pattern.

Data on the amount of cohesive sediment entering the Southeast Black Sea from the Degirmendere River, under the influence of the predominant north-west winds and during the transition from high flow seasons to low flow seasons in different seasons, given by Taş[8], was incorporated into the POMSED model as follows 448 mg/l, 199 mg/l, 110 mg/l, and 39 mg/l. Model results are given in Figure 5.

The amount of cohesive sediments entering the sea is 448 mg/l, the dominant northwest wind with 7 m/s force, high sediment drifts velocity, the predominant surface circulation, and the west-east current in the Southeast Black Sea are incorporated into the model. The model results determined that the cohesive sediment concentration in the marine environment accumulates in intense amounts in the eastern part of the river entrance and from the open to the coastal areas (Fig. 5a). Due to the high amount of cohesive sediments entering the sea, the increased sediment drifts velocity, and the effect of the west to east current the cohesive sediments have accumulated intensely in the east of the study area and the coastal regions. Considering cohesive sediments dispersed in a broader area in the high-flow season (high sediment drift velocity), the total cohesive sediment particles count in the study area is much higher than in the low-flow (low sediment drift velocity) season.

When the amount of cohesive sediment entering the sea is reduced keeping other parameters constant (the dominant surface circulation, the current in the Southeastern Black Sea from west to east, and under the effect of the wind pattern), the cohesive sediments have generally accumulated on the Georgian borders of the Black Sea (Fig. 5b). As the amount of cohesive sediment entering the sea from the river's mouth is reduced, the sediment concentration in the marine environment decreases proportionately. They also accumulate sediments on the Georgian borders of the Black Sea (Fig. 5c, d). It is clear that sediment drift velocity, predominant winds, and currents affect the distribution and concentration of cohesive sediment on the sea surface.

The amount of cohesive sediment (448 mg/l, 199 mg/l, 110 mg/l, and 39 mg/l) entering the Southeastern Black Sea from the Degirmendere River is constant. The results obtained when examining the advection-dispersion, accumulation, and deposition areas of cohesive sediments in the marine environment for low sediment drift velocity under the effect of the dominant surface circulation and dominant northwest wind, which are kept constant, are shown in Figure 6. Since the drift velocity of cohesive sediments entering the sea from the river is low, cohesive sediments have accumulated at the river's mouth due to the dominant surface circulation and effect of the wind pattern. As the sediment drift velocity (river flow velocity)

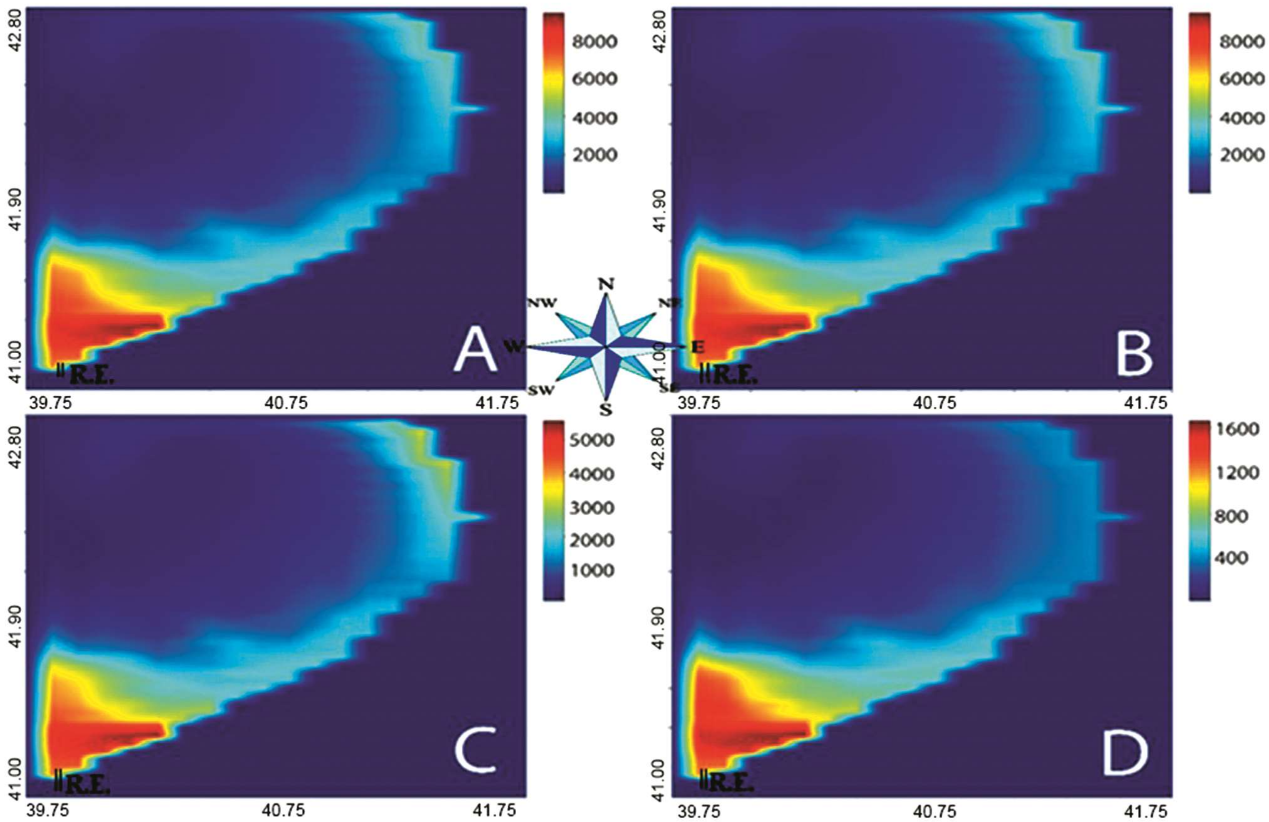

Fig. 6 — Snapshots of cohesive sediment distribution on Southeastern Black Sea for low sediment drift velocity

decreases gradually, cohesive sediments accumulate in large amounts at the river mouth. No matter how high the amount of sediment entering the river, the accumulation occurs at the river's mouth, and only the concentration amount in the marine environment changes (Fig. 6a – d). It has been determined that the sediment drift velocity has the most significant effect on the accumulation areas of cohesive sediments in the marine environment.

When the direction of arrival of the wind is changed to the southwest and other parameters (cohesive sediment amount entering the sea, sediment drift velocity, and dominant surface circulation) are kept constant, and the amount of cohesive sediment entering the sea was increased, the accumulation occurred intensely offshore with the effect of the direction of the wind and the anticyclone cycle (Fig. 7). At the same time, the accumulation occurred on the Georgian borders of the Black Sea (Fig. 7a). As the amount of cohesive sediment entering the sea decreased, the accumulation moved out offshore towards the Georgian borders of the Black Sea (Fig. 7b). It was found that when the amount of sediment entering the sea was minimized while keeping the other parameters constant, the accumulation of cohesive sediments ultimately occurred on the Georgian borders of the Black Sea (Fig. 7c). The most important reasons for this situation are that the direction of arrival of the wind is southwest, the dominant surface circulation, and the current in the Eastern Black Sea is from west to east.

Degirmendere Basin carries an intense amount of sediment load to the Southeastern Black Sea due to floods, landslides, and erosion. The Trabzon port's existence in the west of the point where Degirmendere River discharges into the sea and the fishermen's shelters in the east increase the importance of determining the advection-dispersion, accumulation, and deposition areas of the transported sediments in the marine environment. Cohesive sediments entering the sea during the high flow seasons (the seasons when the sediment drift velocity is high) accumulate heavily in the breakwaters of the fishermen's shelters and east of the river mouth due to the effect of the dominant northwest wind and the west-to-east current. In the low flow seasons,

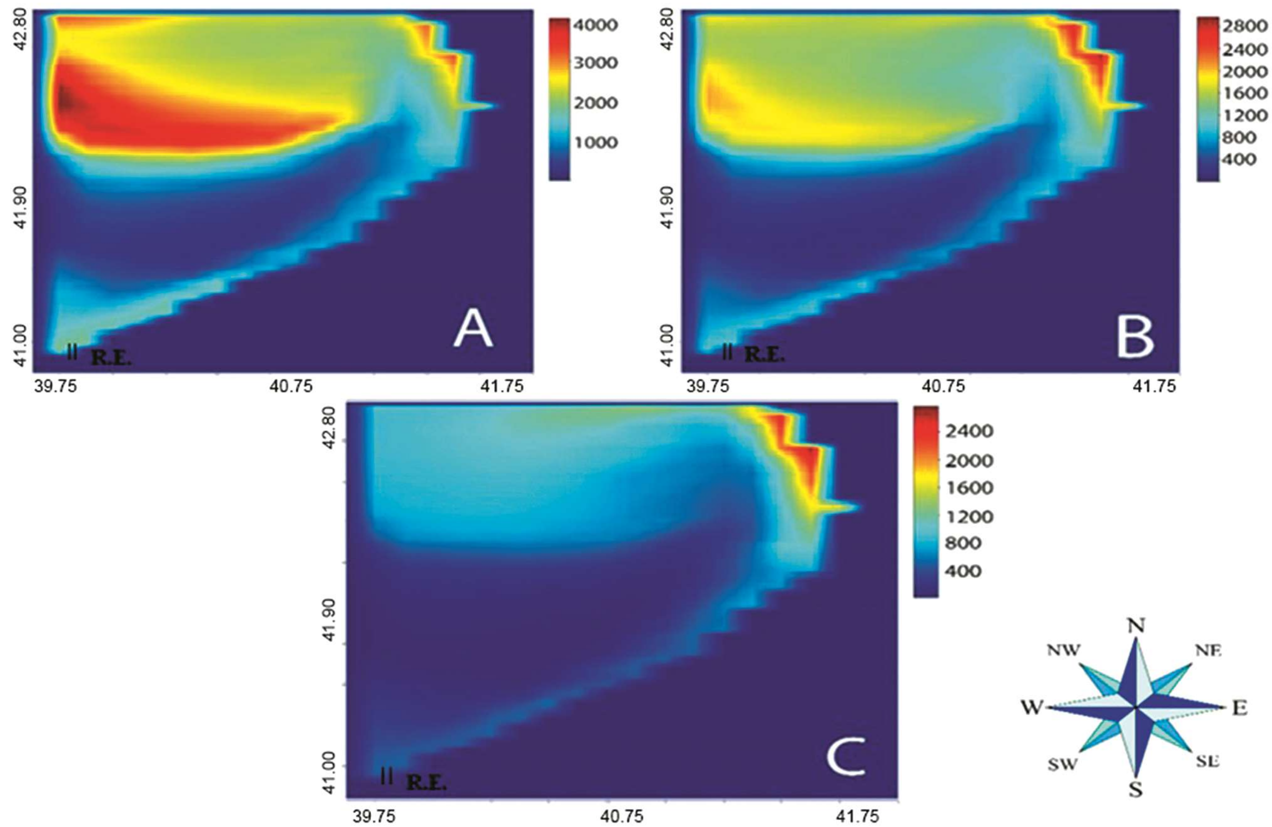

Fig. 7 — Snapshots of cohesive sediment distribution on Southeastern Black Sea for south-west direction active winds

cohesive sediments accumulate at the river mouth and Trabzon port entrance.

In this study, the advection-dispersion, accumulation, and deposition areas of cohesive sediments entering the Southeastern Black Sea from the Degirmendere River have been modeled under different parameters in line with the results obtained from previous studies. The results obtained from the model aimed how the Trabzon port entrance and fishermen's shelters will be affected by the sediment concentration carried out due to possible floods, landslides, and erosion. Another aim of this study is to take necessary precautions in Trabzon port and fishermen's shelters in case of possible future floods, landslides, and erosion. The effects of dams and hydroelectric power plants built on Degirmendere River on the concentration of sediment carried into the marine environment and their impact on coastal erosion have been indirectly investigated. The results obtained from the model will form the basis of possible studies in the future.

Conclusion

This study aimed to provide prior knowledge by modeling the advection-dispersion and accumulation areas of cohesive sediments in the marine environment entering the sea in low-flow and high-flow seasons from Turkey's largest river basin in the Northeast Degirmendere Basin. The accumulation areas of cohesive sediments in the marine environment vary depending on the amount of sediment entering the sea; sediment drift velocity, the direction, and intensity of the dominant wind, the dominant surface circulation, the effect of the anti-cyclone cycle, and high-flow and low-flow seasons. It has been found that the sediment drift velocity under the influence of the predominant northwest winds in the Southeastern Black Sea significantly affects the accumulation of cohesive sediments in the marine environment.

During high-flow seasons, it has been determined that cohesive sediments move from offshore toward the coastal areas and accumulate in the coastal regions. For low sediment drift-velocity, cohesive sediments that enter the sea accumulate densely at the river's mouth. Regardless of the amount of sediment entering the sea in the low-flow seasons, the accumulation areas do not change; only the accumulation density varies. When the southwest wind is effective, cohesive sediments move from offshore towards the Georgian borders of the Black Sea and accumulate in these areas.

The model results can form a basis for coastal interventions on the Southeastern Black Sea coast, planning studies for cleaning the Trabzon port entrance, and risk assessment studies for the area where fishermen's shelters are located. Further, the results presented in current study can be considered while planning exemplification studies in this region.

Conflict of Intrest

The author declared no conflict of interest.

Ethical Statement

The author agreed to the ethical principles.

References

1 Özger M & Kabataş M B, Sediment Load Prediction by Combined Fuzzy Logic-Wavelet Method, *J Hydroinformatics*, 17 (6) (2015) 930–942. https://doi.org/10.2166/hydro.2015.148

2 Berkun M, Akdemir U O & Aras E, Water Runoff, Sediment Transport and Related Impacts in the Southeastern Black Sea Rivers, *Environ Eng Manag J*, 14 (4) (2015) 781-791.

3 Fitri A, Hashim R, Abolfathi S & Abdul Maulud K N, Dynamics of Sediment Transport and Erosion-Deposition Patterns in the Locality of a Detached Low-Crested Breakwater on a Cohesive Coast, *Wate*r, 11 (8) (2019) p. 1721.

4 Akar A, Gokalp E, Bayata H F & Akar O, Determining the Effects of Degirmendere River on Trabzon Harbor after Construction of Black Sea Highway on Black Sea Coast, *Sci Res Essays*, 5 (19) (2010) 2965-2974.

5 Serencam U, *Taşkın Zararları ve Zarar Görebilirlik Analizi: Trabzon Değirmendere Sanayi Mahallesi Örneği*, Doktora Tezi, (Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Trabzon), 2013.

6 Kalkan Y & Alkan R M, *The Areas Covered by Water and Hydrographic Surveying*, (Union of Chambers of Turkish Engineering and Architects Chamber of Survey and Cadastre Engineering, 10th Scientific and Technical Assembly of the Turkish Surveyors, Ankara, Turkey), 2005, (Published in Turkish), http://www.hkmo.org.tr/resimler/ekler/B3D8_115_ek.Pdf

7 Zhang M & Yu G, Critical Conditions of Incipient Motion of Cohesive Sediments, *Water Resour Res*, 53 (9) (2017) 7798-7815. https://doi.org/10.1002/2017WR021066

8 Taş E, *Havza Planlamasi ve Yönetimi: Trabzon Değirmendere Havzasi Örneği*, Yüksek Lisans Tezi, (Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Trabzon), 2014.

9 Yuksek Ö, Önsoy H, Kömürcü M, Kankal M & Akpınar A, Evaluation of The Coastal in Terms of Blacksea Highway, *6th National Coastal Engineering Symposium*, (Published in Turkish), Izmir, 2007, Turkey. http://www.e-kutuphane.imo.org.tr/pdf/3813.pdf

10 Ozseker K, Eruz C, Ciliz S & Mani F, Assessment of Heavy Metal Contribution and Associated Ecological Risk in the Coastal Zone Sediments of the Black Sea: Trabzon, *CLEAN-Soil, Air, Water*, 42 (10) (2014) 1477–1482. Doi: 10.1002/clen.201300785

11 Droppo I G & Krishnappan B G, Modeling of Hydrophobic Cohesive Sediment Transport in the Ells River Alberta, Canada, *J Soils Sediments*, 16 (12) (2016) 2753-2765. Doi: 10.1007/s11368-016-1501-7

12 Zhang J, Chu D, Wang D, Cao A, Lv X, *et al*., Estimation of Spatially Varying Parameters in Three-Dimensional Cohesive Sediment Transport Models by Assimilating Remote Sensing Data, *J Mar Sci Technol*, 23 (2018) 319-332. https://doi.org/10.1007/s00773-017-0477-3

13 Wang D, Zhang J, He X, Chu D, Lv X, *et al*., Parameter Estimation for a Cohesive Sediment Transport Model by Assimilating Satellite Observations in the Hangzhou Bay: Temporal Variations and Spatial Distributions, *Ocean Model*, 121 (2018) 34-48. https://doi.org/10.1016/j.ocemod.2017.11.007

14 Yazir D, *Sediment Taşınımının Matematiksel Modeli*, Yüksek Lisans Tezi, (Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Trabzon), 2016.

15 Sherwood C R, Aretxabaleta A L, Harris C K, Rinehimer J P, Verney R, *et al*., Cohesive and Mixed Sediment in the Regional Ocean Modeling System (ROMS v3.6) Implemented in the Coupled Ocean–Atmosphere–Wave–Sediment Transport Modeling System (COAWST r1234), *Geosci Model Dev*, 11 (5) (2018) 1849–1871. https://doi.org/10.5194/gmd-11-1849-2018

16 Zhao J, Özgen-Xian I, Liang D, Wang T & Hinkelmann R, A Depth-Averaged Non-Cohesive Sediment Transport Model with Improved Discretization of Flux and Source Terms, *J Hydrol*, 570 (2019) 647-665. Doi: 10.1016/j.jhydrol.2018.12.059

17 Vaz N, Vaz L, Serodio J & Dias J M, A Modeling Study of Light Extinction due to Cohesive Sediments in a Shallow Coastal Lagoon Under Well Mixed Conditions, *Sci Total Environ*, 694 (2019) p. 133707. https://doi.org/10.1016/j.scitotenv.2019.133707

18 Lu X, Wang X, Ban X & Singh V P, Transport Characteristics of Non-Cohesive Sediment with Different Hydrological Durations and Sediment Transport Formulas, *J Hydrol*, 591 (2020) p. 125489. Doi: 10.1016/j.jhydrol.2020.125489

19 Wang D, Zhang J, Mao X, Bian C & Zhou Z, Simultaneously Assimilating Multi-Source Observations into A Three-Dimensional Suspended Cohesive Sediment Transport Model by The Adjoint Method in The Bohai Sea, *Estuar Coast Shelf Sci*, 241 (2020) p. 106809. https://doi.org/10.1016/j.ecss.2020.106809

20 Feng Z, Tan G, Xia J, Shu C, Chen P, *et al*., Two-Dimensional Numerical Simulation of Sediment Transport Using Improved Critical Shear Stress Methods,

Int J Sediment Res, 35 (1) (2020) 1-52. https://doi.org/10.1016/j.ijsrc.2019.10.003

21 Shu C, Tan G, Chen P, Wang J & Lv P, Experimental Study on Incipient Shear Stress of Consolidated Cohesive Sediment, *Arab J Geosci*, 13 (18) (2020) p. 964. https://doi.org/10.1007/s12517-020-05978-4

22 Chassagne C & Safar Z, Modelling Flocculation: Towards an Integration in Large-Scale Sediment Transport Models, *Mar Geol*, 430 (2020) p. 106361. Doi: 10.1016/j. margeo.2020.106361

23 Zhu L, Gong W, Zhang H, Huang W & Zhang R, Numerical Study of Sediment Transport Time Scales in an Ebb-Dominated Waterway, *J Hydrol*, 591 (2020) p. 125299. Doi: 10.1016/j.jhydrol.2020.125299

24 Orseau S, Huybrechts N, Tassi P, Damien Pham V B & Klein F, Two-Dimensional Modeling of Fine Sediment Transport with Mixed Sediment and Consolidation: Application to the Gironde Estuary, France, *Int J Sediment Res*, 36 (6) (2021) 736-746. Doi: 10.1016/j.ijsrc.2019.12.005

25 Tayfur G, Empirical, Numerical, and Soft Modelling Approaches for Non-Cohesive Sediment Transport, *Environ Process*, 8 (1) (2021) 1-22. https://doi.org/10.1007/s40710-020-00480-1

26 Egan G, Chang G, McWilliams S, Revelas G, Fringer O, *et al*., Cohesive Sediment Erosion in a Combined Wave-Current Boundary Layer, *JGR Oceans*, 126 (2) (2020) p. e2020JC016655. https://doi.org/10.1029/2020JC016655

27 Stone M, Krishnappan B G, Granger S, Upadhayay H R, Zhang Y, *et al*., Deposition Behaviour of Cohesive Sediment in the Upper River Taw Observatory, Southwest UK: Implications for Management and Modelling, *J Hydrol*, 598 (2021) p. 126145. https://doi.org/10.1016/ j.jhydrol.2021.126145

28 Oguz T, Latun V S, Latif M A, Vladimirov V V, Sur H I, *et al*., Circulation in the surface and intermediate layers of the Black Sea, *Deep Sea Res Part I Oceanogr Res*, 40 (8) (1993) 1597-1612. https://doi.org/10.1016/0967-0637(93)90018-X

29 Özsoy E & Ünlüata Ü, Oceanography of the Black Sea: a review of some recent results, *Earth-Sci Rev*, 42 (4) (1997) 231-272. https://doi.org/10.1016/S0012-8252(97)81859-4

30 Stanev E V, Black Sea dynamics, *Oceanography*, 18 (2) (2005) 56-75.

31 Stanev E V & Kandilarov R, Sediment dynamics in the Black Sea: numerical modelling and remote sensing observations, *Ocean Dyn*, 62 (4) (2012) 533-553. Doi: 10.1007/s10236-012-0520-1

32 Gunduz M, Özsoy E & Hordoir R, A model of Black Sea circulation with strait exchange (2008–2018), *Geosci Model Dev*, 13 (1) (2020) 121-138. https://doi.org/10.5194/gmd-13-121-2020

33 Ghose-Hajra M, McCorquodale J A, Mattson G, Jerolleman D & Filostrat J, Effects of Salinity and Particle Concentration on Sediment Hydrodynamics and Critical Bed-Shear-Stress for Erosion of Fine-Grained Sediments used in Wetland Restoration Projects, in Sediment Dynamics from the Summit to the Sea, New Orleans, Louisiana, USA, *Proc IAHS*, 367 (2015) 435–441. https://doi.org/10.5194/piahs-367-435-2015

34 Partheniades E, Estuarine Sediment Dynamics and Shoaling Processes, In: *Handbook of Coastal and Ocean Engineering*, Vol 3, edited by J Herbick, (Elsevier, New York), 1992, pp. 985 – 1071.

35 Gasper S, *Princeton Ocean Model*, (University of Ljubljana, Faculty of Mathematics and Physics, Department of Physics, Ljubljana), 2006.

36 Yazir D, Unver I, Kose E & Yazıci Z B, Modelling of Cohesive –Sediment Depositional Areas Carried by the Solaklı River to the Eastern Black Sea, *Indian J Geo-Mar Sci*, 47 (3) (2018) 721-728.

37 Mellor G L & Blumberg A F, Modeling Vertical and Horizontal Viscosity and the Sigma Coordinate System, *Monthly Weather Review*, 113 (8) (1985) 1379-1383.

38 HydroQual, Inc., *A primer for ECOMSED Manual*, version 1.3, USA, 2002.

39 Chen B & Wang K, Suspended sediment transport in the offshore near Yangtze Estuary, *J Hydrodyn*, 20 (3) (2008) 373-381.

40 Chu A, Wang Z & deVriend H J, Analysis on Residual Coarse Sediment Transport in estuaries, *Estuar Coast Shelf Sci*, 163 (2015) 194-205. https://doi.org/10.1016 /j.ecss.2015.06.003

41 Gailani J, Ziegler C K & Lick W, The Transport of Sediments in the Fox River, *J Great Lakes Res*, 17 (4) (1991) 479-494. https://doi.org/10.1016/S0380-1330(91)71384-1

42 Krone R B, *Flume Studies of The Transport of sediment in Estuarial Shoaling Processes*, (Final Report, Hydraulic Engr, Lab Sanitary Engr Res Lab, Univ of California, Berkeley) 1962, pp. 110.

43 Bıyık C & İnan H İ (eds), *Çevresel Koruma Amaçlı Olarak Trabzon-Değirmendere Havzası için Mülkiyet Yönetim Fonksiyonlarının Geliştirilmesi ve Kırsal Arazi Düzenlemesinin Modellenmesi (DEVAMOD) Projesi Sonuç Raporu*, (Proje Kodu: 2002.112.006.1, Karadeniz Teknik Üniversitesi, Trabzon). 2007.

44 Korotaev G K, Oguz T, Dorofeyev V L, Demyshev S G, Kubryakov A I, *et al*., Development of Black Sea Nowcasting and Forecasting System, *Ocean Sci*, 7 (5) (2011) 629-649. https://doi.org/10.5194/os-7-629-2011

45 URL-1: DSI, *The General Directorate of State Hydraulic Works, Observatin Data Bank 2021*, Url: http://svtbilgi.dsi.gov.tr/Sorgu.aspx (20.12.2022).