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# Transportation of microplastic during high-flow and low-flow seasons in southeastern Black Sea: A modelling approach

D Yazir*[,a], Y Terzi[b] & C Erüz[c]

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

[b]Karadeniz Technical University, Faculty of Marine Sciences, Department of Fisheries Technology Engineering, 61530, Trabzon, Türkiye

[c]Karadeniz Technical University, Faculty of Marine Sciences, Department of Marine Science and Technology and Engineering, 61530, Trabzon, Türkiye

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

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Predicting the transportation patterns of microplastic particles is crucial for assessing the environmental risks. The present work studied the transportation and accumulation of floating microplastic particles released from the largest river basin (Değirmendere), on the southeastern Black Sea coast. A total of 2 scenarios were simulated for high-flow and low-flow seasons to predict the effect of freshwater input on the concentration, transportation and accumulation patterns of microplastic particles by using a Lagrangian model; the Estuarine, Coastal Ocean Model with Sediment Transport (ECOMSED) model. Microplastic concentration varied between 168 – 1412 particle/m$^3$ and 0 – 843 particle/m$^3$ in the high-flow and low-flow seasons, respectively. Microplastic particles released from the river showed different accumulation patterns with time. However, the particles tended to accumulate on coastal waters in both scenarios. The present study provides a baseline for determining the hotspots for the accumulation of floating microplastic particles to assess optimal sampling locations and risk assessment in the southeastern Black Sea.

[**Keywords**: Black Sea, ECOMSED model, Microplastic, Modelling, Plastic, Transportation]

## Introduction

Plastic became a common material in the modern era, thanks to its durability and low cost of production[1]. The production increased dramatically in the last few decades and reached 359 million tonnes per year in 2018[(ref. 2)]. Despite its high recycling potential, inappropriate disposal and collection of plastic caused them to reach the marine ecosystem. The studies conducted on marine litter pollution address that it is the most common contributor on a global scale[3]. Plastic can be found in the marine ecosystem in the form of macroplastics, mesoplastics and microplastics, depending on particle size[4]. The particles of plastic ≤ 5 mm in size were defined as microplastics[5]. Mainly, there are two types of microplastics based on the source; primary microplastics - the particles manufactured to be of a microplastic size for industrial use, and secondary microplastics - particles that result from degradation or breakdown of larger plastic items in the marine or freshwater environment[6]. The existence of microplastics in the marine ecosystem was reported in the early 1970s for the first time[7]. However, studies on distribution and impacts effectively began in the early 2000s[8]. Since then, researchers focussed on the concentration, distribution and composition in the marine ecosystem and the effects on the aquatic organisms[9]. The most common polymers (*i.e.*, polyethylene, polypropylene and polystyrene) are highly buoyant due to low density compared to seawater. Thus, these particles can be transported long distances from the source by surface currents and winds[10] and create a transboundary problem.

Microplastic particles can absorb persistent organic pollutants and metals and behave as vectors for contaminants in the marine environment[11]. These particles can be transferred directly from water or via the food web[12]. Various studies reported the existence of microplastics in aquatic organisms such as zooplanktons[13], demersal and pelagic fishes[14] and crustaceans[15]. The impacts on aquatic organisms were also reported[16] but more comprehensive research is needed[17]. Additionally, the aquatic organisms intended for human consumption are potential vectors and risks for human health[18].

The Black Sea is a unique ecosystem due to an anoxic zone starting below approximately 150 – 170 m limiting aerobic life. The contamination of the oxygenated water layer is a great threat and is potentially hazardous in contrast to any other sea in the world[19]. Thus, monitoring the pollutants in this unique ecosystem should be a priority for risk assessment and determination of potential removal areas. Plastic pollution in the Black Sea is well-documented in previous studies[20,21]. A 2016 study revealed the existence of microplastics and probable entrance to the food web in the Black Sea ecosystem[22]. Various studies reported the microplastic concentration in seawater and sediments in the Black Sea[23,24]. Moreover, microplastics were found in the gastrointestinal tract of the European anchovy (*Engraulis encrasicolus*),[25,26] which is a filter feeder and the most important commercial fish for Black Sea fisheries, Mediterranean mussels (*Mytilus galloprovincialis*)[27] and stripped venus clam (*Chamelea gallina*)[28] in the Black Sea.

Freshwater ecosystems are one of the most significant sources and pathways for microplastics[29]. Sampling and evaluating the pollutants, including microplastics in the marine environment are effortful and expensive processes. Mathematical models can be employed to reduce cost and effort. In this study, a model is created to predict the transportation and accumulation of microplastic particles in the southeastern Black Sea during high-flow (April) and low-flow (August) seasons. Değirmendere River, the largest river basin in the Eastern Black Sea Region of Turkey, was determined as the release point. *In-situ* data on the emission of microplastics from rivers are lacking from the southeastern Black Sea coast. Thus, the current work attempted to provide a theoretical assessment of the fate of microplastic particles in the study area. It can be a baseline for future field studies, risk assessment and potential removal activities.

## Materials and Methods

The fate and future trends of the microplastics can be assessed through the results obtained from the numerical models[30]. The transportation of the microplastic particles released from the Değirmendere River in the southeastern Black Sea was modelled using ECOMSED.

### Study area

Değirmendere River mouth (41°0'9.04" N, 39°45'25.33" E), which has the largest river basin (1053 km$^2$) within the Eastern Black Sea region of Turkey, was chosen as the microplastic release point (Fig. 1). The basin includes Ortahisar and Maçka districts, Çağlayan, Akoluk, Çukurçayır, Esiroğlu and Atasu towns and a total of 80 village settlements. The

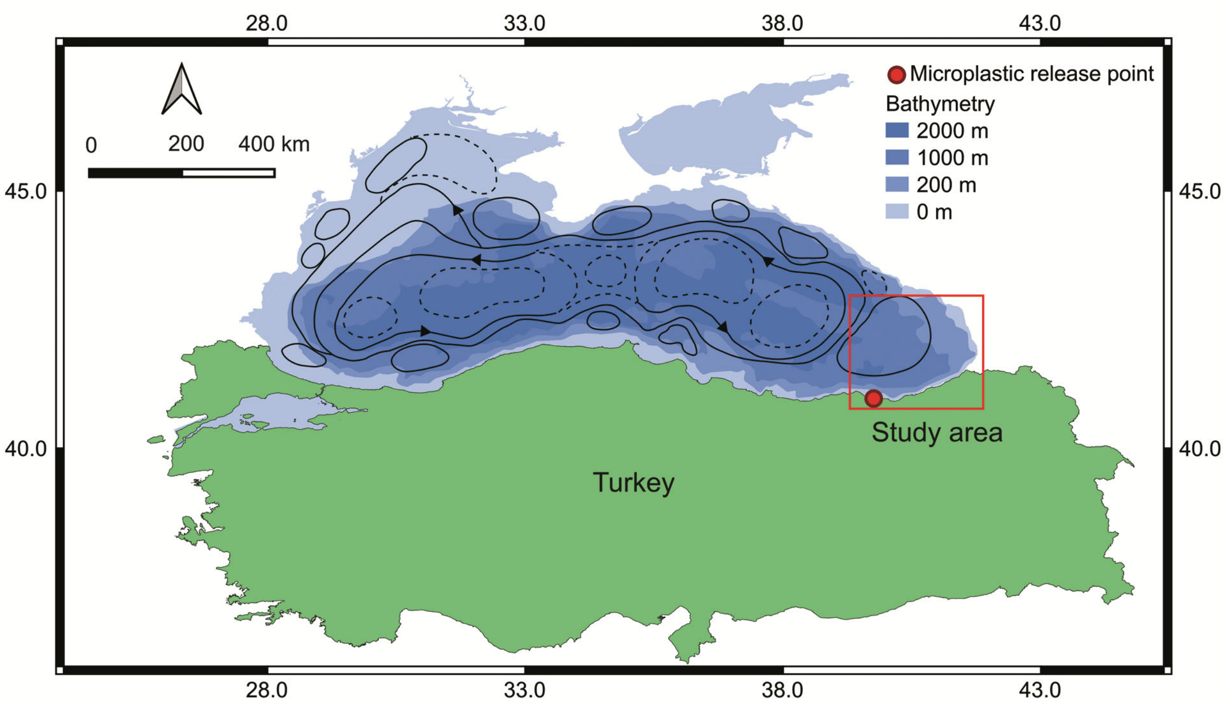


Fig. 1 — Map of the study area and microplastic release point

growing population of Trabzon province also increases the use of the Değirmendere Basin, especially the downstream part of the basin; urban, industrial, and mining structures are climbing rapidly. In the absence of wastewater treatment plants in the region, wastewater, pesticides, and fertilizers are being discharged directly to the Black Sea without any treatment. The hydrodynamics of the Black Sea is well-documented in the literature[31]. The study area is hydrodynamically under the influence of the central cyclonic cycle of the Black Sea, which is active throughout the year and is affected by anticyclonic meandering rim current. Moreover, the Batumi anticyclone, one of the most intense eddy formations, remains active from March to October in the study area[32].

**The modelling framework**

Two different scenarios were applied to predict the microplastic transportation and accumulation in high-flow (April) and low-flow (August) seasons. The flow rate of the Değirmendere river was 41.3 $m^3$/s and 5.1 $m^3$/s for high-flow and low-flow seasons, respectively[33]. It is assumed that the microplastic concentration in the seawater (C) was zero at the start of the modelling ($t$ = 0). There is no empirical data on the concentration of the released microplastic particles from the rivers of the northern part of Turkey. The method by Genc *et. al.*[34] was adopted to determine the released particle concentration from the river. The model was run with different released particle concentrations to reach closer to the concentration (600 – 1200 particle/$m^3$) presented by Aytan *et. al.*[22], whose study area was also the southeastern Black Sea coast. The released particle concentration was set to 90 particle/$m^3$ and assumed constant and continuous for 30 days. Factors like stokes drift, biofouling on the particles, reactions with seawater, and injection by the marine organisms were ignored. The snapshots of the scenarios were taken on the 10, 20 and 30 days to evaluate the effect of time on the distribution and concentration of the particles. The data for the hydrodynamic module was retrieved from free online sources. The 10 m wind data for April 2019 and August 2019 was collected from the European Centre for Medium-Range Weather Forecasts (ECMWF) (http://www.ecmwf.int) based on 6-hourly records. Circulation data for the same dates was fetched from Copernicus (https://marine.copernicus.eu/). An overall presentation of the average data is given in Figure 2.

**ECOMSED model**

ECOMSED is a particle transport and hydrodynamic model used to calculate deposition, water circulation, transport, and re-suspension of microplastic, non-cohesive, and cohesive particles[35]. The model can simulate the movement of buoyant particles and suspended sediments in the coastal and estuarine marine systems. The proficiencies of the model are the inclusion of wind wave effects on hydrodynamics and sediment transport, dissolved tracer transport (conservative or first-order decay) and neutrally buoyant particle tracking. The hydrodynamic module, SED module and particle tracking module of the ECOMSED were utilised in this analysis.

**Hydrodynamic module**

The hydrodynamic module, Estuarine and Coastal Ocean Model (ECOM) is a time-dependent, three-dimensional model developed by Blumberg *et al.*[36]. Comprehensive comparisons were performed to assess the predictive capabilities of the module. The data produced by the model was found to be closer to the predominant physics[35].

**Particle transportation and tracking**

Discrete, neutrally buoyant and conservative particles released from single or multiple points can be monitored through the particle transportation module. The transport of microplastic particles was simulated using this module in ECOMSED. The microplastic particles were advected using a Lagrangian technique, and the effects of turbulent diffusion were simulated with a random walk procedure[36].

**Vertical coordinate representation**

Certain disadvantages of the ordinary ($x$, $y$, $z$) coordinate system were reported in large bathymetric irregularities. Thus, a new set of independent variables that transforms the bottom and surface into coordinate surfaces named σ-coordinate system[37] was determined.

The governing internal and external mode equations were transformed from coordinates ($x$, $y$, $z$) to ($x^*$, $y^*$, $\sigma$, $t^*$).

$$x^* = x\,,\; y^* = y\,, \sigma = \frac{z-\eta}{H+\eta}\,, t^* = t \quad \ldots (1)$$

$$D \equiv H + \eta \quad \ldots (2)$$

By applying the chain rule; relationships below linking derivatives in the old system to those in the new system were obtained:

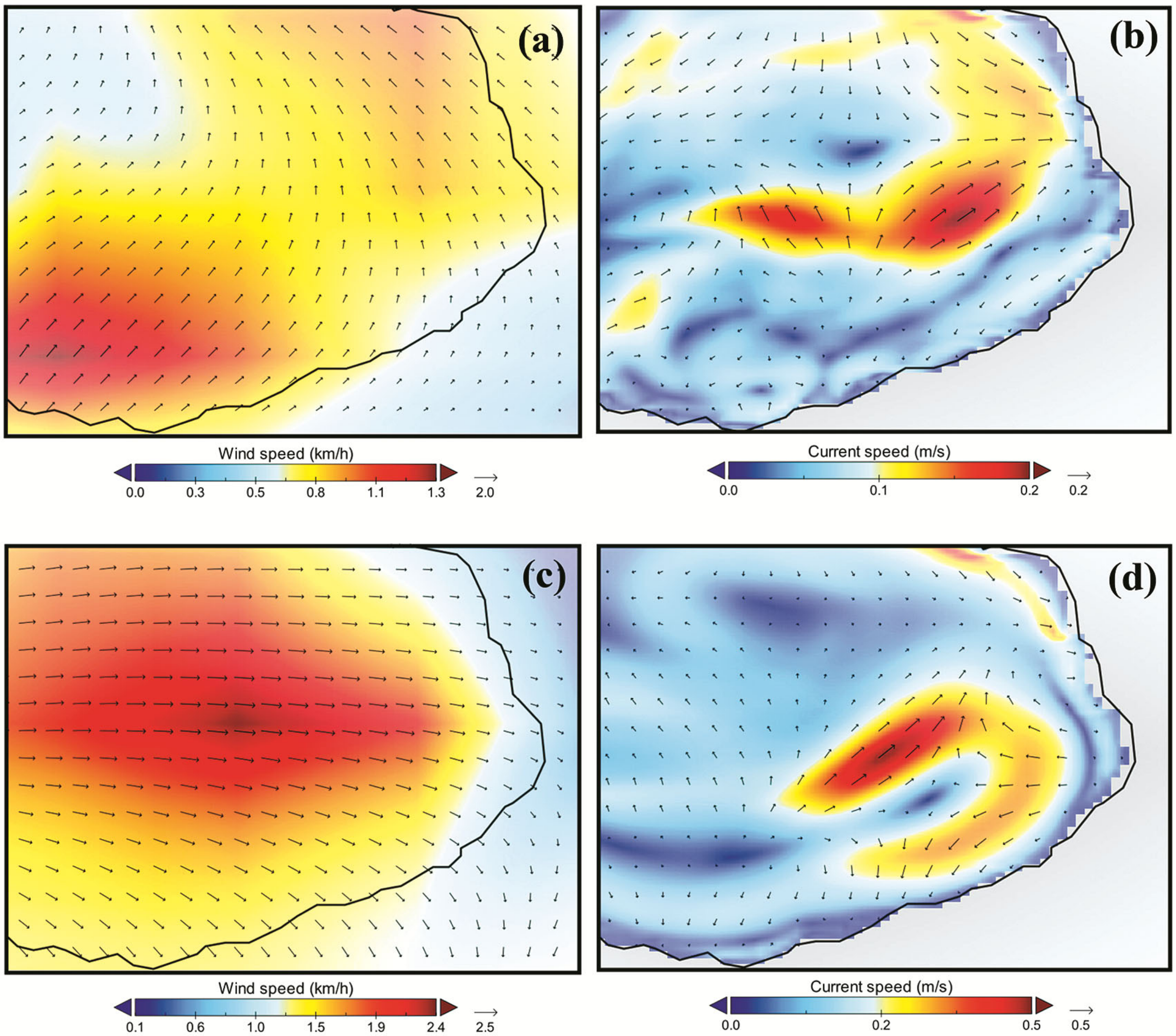


Fig. 2 — Mountly mean wind, and current during high-flow (a, b) and low-flow (c, d) seasons

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

$$\frac{\partial G}{\partial y} = \frac{\partial G}{\partial y^*} - \frac{\partial G}{\partial \sigma}\left[\frac{\sigma}{D}\frac{\partial D}{\partial y^*} + \frac{1}{D}\frac{\partial \eta}{\partial y^*}\right] \quad \dots (4)$$

$$\frac{\partial G}{\partial t} = \frac{\partial G}{\partial t^*} - \frac{\partial G}{\partial \sigma}\left[\frac{\sigma}{D}\frac{\partial D}{\partial t^*} + \frac{1}{D}\frac{\partial \eta}{\partial t^*}\right] \quad \dots (5)$$

$$\frac{\partial G}{\partial z} = \frac{\partial G}{\partial \sigma}\frac{\partial \sigma}{\partial t} = \frac{1}{D}\frac{\partial G}{\partial \sigma} \quad \dots (6)$$

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

A new vertical velocity can now be defined as:

$$\omega \equiv w - U\omega\sigma\frac{\partial D}{\partial x^*} + \frac{\partial \eta}{\partial x^*} - V\sigma\frac{\partial D}{\partial y^*} + \frac{\partial \eta}{\partial y^*} - \left(\sigma\frac{\partial D}{\partial t^*} + \frac{\partial \eta}{\partial t^*}\right) \quad \dots (7)$$

which transforms the boundary conditions,

$$\omega(x^*, y^*, 0, t^*) = 0\,, \omega(x^*, y^*, -1, t^*) = 0 \quad \dots (8)$$

Also, any vertically integrated quantity, for example, $G$, appears as[38]

$$\bar{G} = \int_{-1}^{0} G\, d\sigma \quad \dots (9)$$

**Particle tracking module**

The particle tracking module is beneficial for studying the trajectories of floating objects like microplastics. The particles entering the sea from the river can be monitored via this module. The latter was utilised in this study. The particle movement was determined by exploiting the equivalency between tracking particles and solving a mass transport equation for a conservative substance[39]. Introducing the σ transformation in the vertical:

$$\sigma = \frac{z-\eta}{H+\eta} \quad \dots (10)$$

Where, $H$ ($x$, $y$) is the water depth, $\eta(x, y)$ is the surface elevation and $D \equiv H + \eta$, the transport equation for a conservative tracer in an orthogonal curvilinear coordinate system $(\xi_1, \xi_2, \sigma)$ can be written as[36]:

$$h_1 h_2 \frac{\partial(DC)}{\partial t} + \frac{\partial}{\partial \zeta_1}(h_2 U_1 DC) + \frac{\partial}{\partial \zeta_2}(h_1 U_2 DC) + h_1 h_2 \frac{\partial(\omega C)}{\partial \sigma} = \frac{\partial}{\partial \zeta_1}\left(\frac{h_2}{h_1} A_H D \frac{\partial C}{\partial \zeta_1}\right) + \frac{\partial}{\partial \zeta_2}\left(\frac{h_1}{h_2} A_H D \frac{\partial C}{\partial \zeta_2}\right) + \frac{h_1 h_2}{D}\frac{\partial}{\partial \sigma}\left(K_H \frac{\partial C}{\partial \sigma}\right) \quad \dots (11)$$

Where,

$$\omega = W - \frac{1}{h_1 h_2}\left[h_2 U_1 \left(\sigma \frac{\partial D}{\partial \zeta_1} + \frac{\partial \eta}{\partial \zeta_1}\right) + h_1 U_2 \left(\sigma \frac{\partial D}{\partial \zeta_2} + \frac{\partial \eta}{\partial \zeta_2}\right)\right] - \left(\sigma \frac{\partial D}{\partial t} + \frac{\partial \eta}{\partial t}\right) \quad \dots (12)$$

$C$ is the concentration, $h_1$ and $h_2$ are the metrics of the unit grid cell in the $\zeta_1$ and $\zeta_2$ directions, and $U_1$ and $U_2$ are the velocity components along the $\zeta_2$ and $\zeta_2$ directions. Adding:

$$\frac{\partial}{\partial \zeta_1}\left[\frac{\partial}{\partial \zeta_1}\left(\frac{A_H}{h^2{}_1} h_1 h_2 D\right) C\right] + \frac{\partial}{\partial \zeta_2}\left[\frac{\partial}{\partial \zeta_2}\left(\frac{A_H}{h^2{}_2} h_1 h_2 D\right) C\right] + \frac{\partial}{\partial \sigma}\left[\frac{\partial}{\partial \sigma}\left(\frac{K_H}{D^2} h_1 h_2 D\right) C\right] \quad \dots (13)$$

On both sides of Equation (11) and rearranging it, the transport equation becomes

$$\frac{\partial}{\partial t}(h_1 h_2 DC) + \frac{\partial}{\partial \zeta_1}\left\{\left[\frac{U_1}{h_1} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \zeta_1}\left(\frac{A_H}{h^2{}_2} h_1 h_2 D)\right] h_1 h_2 DC\right\} + \frac{\partial}{\partial \zeta_2}\left\{\left[\frac{U_2}{h_2} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \zeta_2}\left(\frac{A_H}{h^2{}_2} h_1 h_2 D)\right] h_1 h_2 DC\right\} + \frac{\partial}{\partial \sigma}\left\{\left[\frac{\omega}{D} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \sigma}\left(\frac{K_H}{D^2} h_1 h_2 D)\right] h_1 h_2 DC\right\} = \frac{\partial}{\partial \zeta^2{}_1}\left(\frac{A_H}{h^2{}_1} h_1 h_2 DC\right) + \frac{\partial}{\partial \zeta^2{}_2}\left(\frac{A_H}{h^2{}_1} h_1 h_2 DC\right) + \frac{\partial}{\partial^2 \sigma}\left(\frac{K_H}{D^2} h_1 h_2 DC\right) \quad \dots (14)$$

#### Governing equation

The three-dimensional pollutant transport equation applied for microplastics is given in Equation (15).

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} - \frac{\partial C}{\partial z} + (w - w_p)\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right) + k_p C + S \quad \dots (15)$$

Where, $C$ is the microplastic concentration; $x$ & $y$ are the horizontal coordinates and $z$ is the vertical coordinate; $u$, $v$, and $w$ are the current velocities in the $x$, $y$ & $z$ coordinates, respectively; $w_p$ is the particle settling velocity; $t$ is time; $D_x$, $D_y$ and $D_z$ are the coefficients of turbulence diffusion in $x$, $y$ and z coordinates; $k_p$ is the reaction coefficient and $S$ is the source concentration. The microplastic concentration $C$ is generally given as either $g/m^3$. If the diameter of the microplastic particle is denoted as $d$, and its density is indicated as $\rho_p$, then the microplastic concentration $C$ is given as in Equation (16):

$$C = n\rho_p \left(\frac{\pi}{6}\right) d^3 \quad \dots (16)$$

Where, $n$ is the particle number given as particles/m$^3$[ref. 34].

In modelling the behaviour of microplastics in the marine environment, the density and precipitation rate of the plastic studied is important. Therefore, in the modelling study, Eq. (17) is applied.

$$w_s = \frac{\upsilon}{d} d_*^3 [38.1 + 0.93 d_*^{12/7}]^{-7/8} \quad \dots (17)$$

Where,

$$d_* = \left(\frac{\Delta g}{\upsilon^2}\right)^{1/3} d \text{ and } \Delta = \frac{\rho_s}{\rho} - 1 \quad \dots (18)$$

Where, $\rho_s$ is the density of microplastic particles, $\rho$ is the density of the fluid, and $\upsilon$ is the kinematic viscosity of the fluid[34].

Thanks to Equation (15), the behaviour of microplastics entering the sea from the river in the marine environment is modelled.

## Results and Discussion

The transportation and accumulation of the floating microplastic particles released from the Değirmendere River in the southeastern Black sea based on high-flow (April) and low-flow (August) seasons were modelled using the particles tracking module of ECOMSED. The continuous release rate was set to 90 particles/m$^3$ for 30 days. Microplastic concentration was predicted as 168 – 1412 particles/m$^3$ in the high-flow season and 0 – 843 particles/m$^3$ in the low-flow season. Maximum concentration increased with time in both scenarios. Despite the flow rate of the river being almost 8 times higher in the high-flow season, the maximum concentration was 67.5 % higher in contrast to the low-flow season. Considering microplastic particles dispersed in a wider area during the high-flow season (Fig. 3), the total particle count in the study area was much higher compared to the low-flow season. In scenario 1, the transportation and accumulation of the microplastic particles in the high-flow (April) season were predicted. According to data retrieved from ECMW and Copernicus, SW and W winds and E and NE surface currents were dominant in the study area in April 2019 (Fig. 2a, b). On the 10$^{th}$ day of the simulation, the microplastic particles spread north of the release point at 80 – 169 particles/m$^3$ concentration (Fig. 3S1). The particles accumulated in the north of the study area and showed a significant accumulation pattern on the 20$^{th}$ day (Fig. 3S2). At the end of scenario 1, under the influence of the dominant surface circulation and wind pattern, the accumulation of microplastic particles on the northeast of the release point was observed. The predicted concentration varied between 852 to 1412 particles/m$^3$ (Fig. 3S3). In scenario 2, the transportation and accumulation of microplastics in the low-flow (August) season were predicted. In August 2019, the study area was influenced by W and NW winds and S and SW surface currents (Fig. 2c, d). Released particles accumulated at the east of the release point with a concentration of 144 – 223 particles/m$^3$ on the 10$^{th}$ day of the simulation (Fig. 3S4). On the 20$^{th}$ day of scenario 2, the particles relatively accumulated in the coastal area and spread (Fig. 3S5). After 30 days of continuous release, the particles assimilated on the Georgian coast of the Black Sea under the influence of the dominant surface circulation and wind pattern (Fig. 3S6).

The distribution of microplastic particles showed different patterns between high-flow and low-flow seasons because of the different predominant ways of surface currents and winds. Aytan *et al.*[22] reported significantly different concentrations of microplastic particles in different seasons (November 2014 and February 2015) on the southeastern Black Sea. It is clear that the seasonal differences in the predominant winds and currents affect the distribution and concentration on the sea surface. The microplastic particles piled up in the coastal zone of the study area after 30 days of continuous release. This can be explained by the phenomenon suggested by Stanev *et al.*[40,41], which explains the movement of the water masses in the Black Sea. Accordingly, the surface water is prone to be displaced with the water from the interior of the cycle by the Ekman drift, and upwelling replaces the water in the basin interior. Thus, the microplastic particles tend to drift throughout the coast from the interior of the anticyclonic cycle.

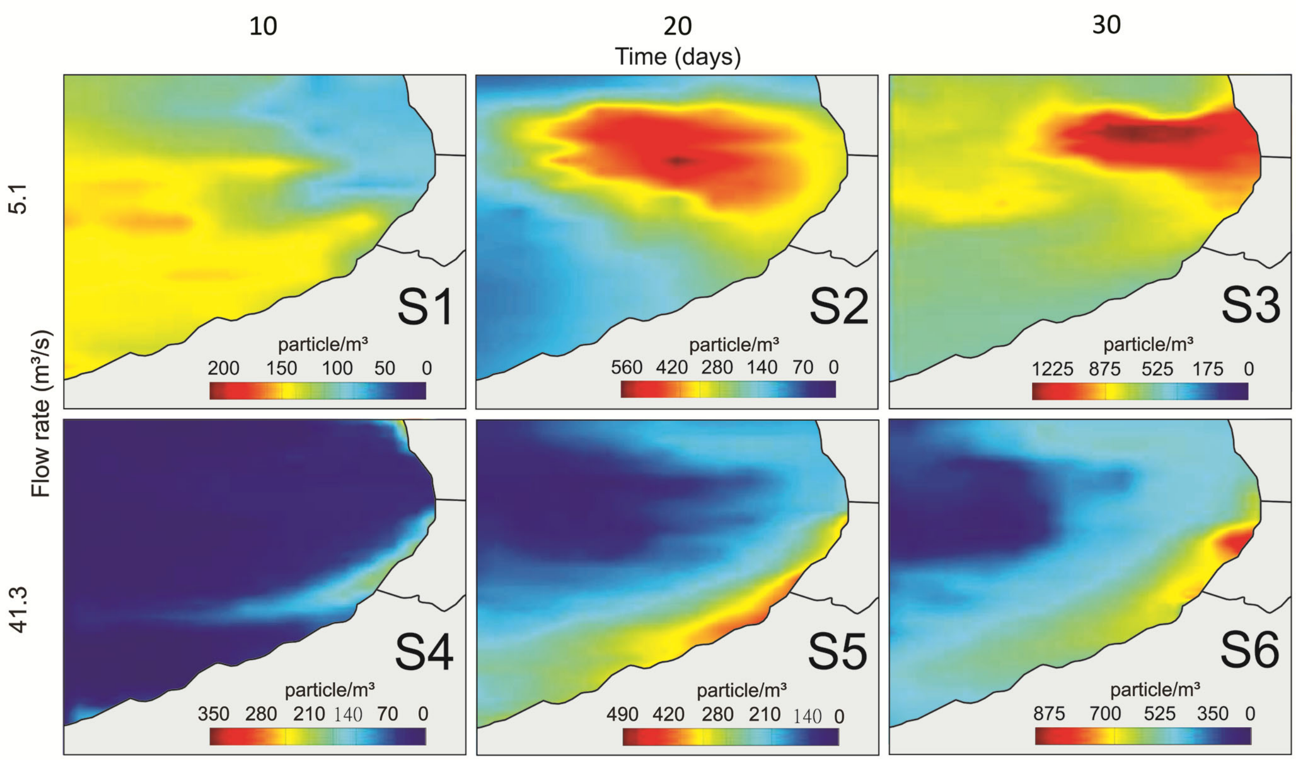


Fig. 3 — Snapshots of microplastic distribution on southeastern Black Sea in high-flow (S1, S2, and S3) and low-flow (S4, S5, and S6)

Many studies presented the distribution and concentration of the microplastic particles in the surface waters of the Black Sea[22,23,42]. The current work indicates that microplastic particles released from the rivers on the southeastern Black Sea are prone to accumulate in coastal areas. Coastal zones are vital spawning and nursery areas for many aquatic organisms that are economically and ecologically important in the Black Sea[43]. Ingestion of microplastic particles by several marine fish species larvae was reported in recent studies. The particles in the nursery areas can be lethal, especially for zooplanktons and fishes at the larval stage by blocking and filling their digestive tract[44]. Significant toxic effects on fish larvae exposed to microplastic particles, especially in the coastal areas, were reported by Pannetier *et al.*[45]. However, very little is known about the interaction of marine organisms with plastic in the Black Sea[46]. Considering the continuous input from freshwater sources, the increased levels of microplastic particles may be a risk to these organisms. Besides, high concentrations and accumulation trends of floating litter that may be the source of secondary microplastics were reported on the southern coast of the Black Sea in large-scale modelling studies[47,48].

## Conclusion

The present study provides information on the transportation and distribution patterns of microplastics released from the largest river basin (Değirmendere) in the northeast of Turkey during low-flow and high-flow seasons. Microplastics mostly contaminated the coastal zone with an increasing concentration over time. The distribution patterns changed over time and were different in low-flow and high-flow seasons. This variability should be considered while planning sampling studies in the area. Thus, our model can be a baseline for field studies, risk assessment, and determination of potential removal points in the southeastern Black Sea.

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## Conflict of Interest

The authors have declared no conflict of interest.

## Ethical Statement

This is to certify that the manuscript is original and has not been submitted elsewhere. This submission has been approved by all co-authors and has contributed sufficiently to share collective accountability for the results.

## Author Contributions

DY: Conceptualization, methodology, formal analysis, writing - review & editing; YT: Conceptualization, software, writing - original draft, and visualization; and CE: Investigation, writing - review & editing.

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