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# Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport

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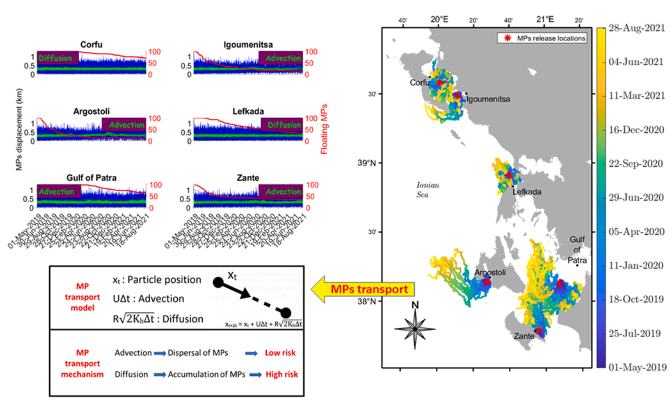
## HIGHLIGHTS

- NE Ionian Sea's first study on microplastic particles' transport.
- Diffusion controls the accumulation of floating microplastic particles in the marine environment.
- 63% of floating microplastic particles were beached within the 2.3 years of the simulation.
- Beaching of particles occurs mostly within the first weeks after being released.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The Mediterranean Sea is among the most affected areas of our planet by microplastic (MP) pollution. However, some regions are still underrepresented in the current literature. This work studied the fate of microplastics (MPs) released from major populated areas within the NE Ionian Sea, an area that contains highly significant biodiversity. This was accomplished by incorporating oceanographic data into a Lagrangian particle-tracking numerical model that simulated the transport of MP particles for the interval of 27 months. The findings report a high possibility of beaching within the first weeks of the simulation for most locations, where 63 % of MPs were beached and 37 % were still floating at the end of the simulation. Seaward transport and eddy diffusivity are the controlling mechanisms of the MP transport, with diffusion being the primary force controlling the movement of MP particles in 1/3 of the simulated regions. This is highly significant, because in areas where diffusion is the main mechanism controlling MP transport, accumulation of floating MP particles is occurring, as reported in previous studies. The MPs' transport and beaching behavior, as well as the observed residence times, were used to determine the threat level that MPs pose to the biodiversity of specific areas.

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## 1. Statement of Environmental Implication

Microplastics (MPs) are hazardous materials posing a threat to marine organisms and humans. Studies have shown that microplastics absorb toxic chemicals, turning their chemical characteristics (from manufacturing) into a “toxic cocktail” of contaminants (Bergmann et al., 2015). MPs are being ingested by marine organisms and accumulate chemical contaminants to higher-level organisms through the food chain (Kershaw, 2015). MPs were found in many commercially exploited marine species(mussels, fish, shrimp), creating potential risks regarding seafood consumption (Hantoro et al., 2019). This work provides information regarding the microplastic (MP) pollution threat level for marine biota and the factors influencing the fate and accumulation of MPs, which can alert the authorities to inform policies to reduce the plastic pollution.

## 2. Introduction

Plastic pollution in the marine environment has reached unprecedented limits, with over 269,000 tons of plastic debris floating on the surface of the oceans (Eriksen et al., 2014). Plastic debris enters the marine environment as macroplastics (particles $\geq$ 5 mm), and fragmentation and degradation due to physical, chemical, and biological processes (UV-photooxidation, chemical breakdown, ingestion by marine organisms, wave mechanics etc.), leads to their reduction to MPs (particles $\leq$ 5 mm) (Thompson et al., 2004; Ioakeimidis et al., 2016; Cole et al., 2016).

In coastal areas, most of the marine plastic debris originates from land sources (harbor areas, rivers, touristic beaches, cities, industrial areas, and storm water runoff) (Moore et al., 2011; Cheung et al., 2016; Kalogerakis et al., 2017; Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017; Zhao et al., 2015; Auta et al., 2017; Yu et al., 2018), and can be found in the whole water column from the surface of the ocean to its deepest regions (Van Cauwenberghe et al., 2013; Lusher et al., 2015; Courtene-Jones et al., 2017; Morgana et al., 2018). Studies have shown that marine plastic abundance in coastal regions is significantly correlated with the coastal population and exhibits great spatial and temporal variations (Zhao et al., 2015; Pedrotti et al., 2016; Lots et al., 2017).

Several studies have reported the negative effects of MPs in the marine ecosystem and human health, as they absorb toxic chemical contaminants (Lee et al., 2014; Koelmans et al., 2016; Torres et al., 2020), are being ingested by marine organisms (such as bivalves, fish, seabirds, mussels, corals, whales, and plankton) (Thiel et al., 2018; Lusher et al., 2013; Hall et al., 2015; Browne et al., 2008; Frias et al., 2014; Fossi et al., 2012; Digka et al., 2018), entering the food chain, and being accumulated even in humans (with this accumulation being quantified to a credit card worth of plastic per year (de Wit and Bigaud, 2019; Galloway, 2015). Also, as a most recent discovery, MPs are known to play a role in the carbon cycle (Galgani et al., 2019; Taipale et al., 2019). However, the factors affecting the MPs abundance in the marine environment are still underrepresented in the current literature (Adamopoulou et al., 2021).

The Mediterranean Sea is among the most affected areas of our planet by microplastic pollution, as predicted by numerical models (Lebreton et al., 2012; Van Sebille et al., 2015; Guerrini et al., 2021), and validated by sampling campaigns (Suaria et al., 2016). Unfortunately, this agreement between numerical models and field measurements raises concerns regarding the impact of microplastic pollution on the already heavily impacted marine biodiversity of the Mediterranean Sea (Micheli et al., 2013).

In order to investigate the spatial and temporal distribution of microplastics in the marine environment, sampling efforts (including net tows, boat trawls, beach cleanups, sediment samples, etc.) occurred at different places and times (Eriksen et al., 2013; Eriksen et al., 2014; Lebreton et al., 2012). However, issues concerning the net sizes, sampling protocols, recording standards, time, weather, and costs (Law, 2017; Lebreton et al., 2012; Simantiris et al., 2022) render traditional methods incapable of accurately estimating the distribution of MPs in the marine environment (Law, 2017), and constrain them in small areas and timescales (Hardesty et al., 2017). Thus, numerical modeling has been applied in studies on the oceans and lakes around the globe as an effective tool for studying microplastic pollution in the marine environment (Lebreton et al., 2012; Maximenko et al., 2012; Van Sebille et al., 2012).

Numerical modeling has proven to be an essential tool for describing the transport of MPs in the surface of the ocean, and has been widely used around the world in studies aiming to investigate the garbage catches (Maximenko et al., 2012; Van Sebille et al., 2012), estimate the abundance of plastic in the ocean (Hoffman and Hittinger, 2017; Koelmans et al., 2016) or track the fate of plastic in the marine environment from a known source (Lebreton and Borrero, 2013). Several studies on the “garbage patches” of the subtropical gyres have exhibited similar surface patterns indicating the robustness of numerical modeling (Eriksen et al., 2014; Lebreton et al., 2012; Maximenko et al., 2012; Van Sebille et al., 2012; Van Sebille et al., 2015). In order to track the floating marine plastic debris’ trajectories in the ocean, studies apply existing Lagrangian models (used for tracking oil spills, larvae, sediment transport, etc.), that include currents and diffusion processes (Lebreton et al., 2012; Potemra, 2012; Eriksen et al., 2013; Law et al., 2010). Langragian particle-tracking models coupled to circulation models have been widely used for investigating microplastic sources, fate and trajectories in the marine environment (Liubartseva et al., 2016; Liubartseva et al., 2018; Isobe et al., 2009; Martinez et al., 2009; Yoon et al., 2010; Lebreton et al., 2012; Neumann et al., 2014; Mansui et al., 2015; Carlson et al., 2017; Kubota, 1994). Also, transport models assist in understanding the spatial and temporal variability of MP accumulation in the marine environment and inform policies (Braunschweig et al., 2003; Mateus et al., 2012). Although many studies using transport models have aimed at evaluating the point sources of MPs in the marine environment (Reisser et al., 2013; Martinez et al., 2009; Lebreton et al., 2012; Maximenko et al., 2012), recent studies aim more toward investigating the effect of MP accumulation on estuarine and marine habitats (Hardesty et al., 2017).

Although MP mobility is influenced by several factors that can lead to the sinking of MP particles, studies have shown that the majority of plastic debris is buoyant and mostly concentrated at the surface of the oceans (Kukulka et al., 2012). Floating MPs are subject to transportation by surface currents and diffusion, and can be carried thousands of kilometers away from their source, depending on the advective and diffusive processes. Hence, highly populated areas and infrastructure near the coasts are becoming a threat not only to the nearby marine environment but to the whole planet (Wichmann et al., 2019). In this work, we conduct an investigation of the fate of floating MPs originating from major populated areas on the land surrounding the Ionian Archipelago. The Ionian Archipelago contains 21 regions of highly important biodiversity protected by NATURA 2000 that cover an area greater than 3500 km$^2$ containing numerous endangered species (Natura2000, 2016). However, studies on the MP pollution in this region are very limited. This study will show the potential threat of MP pollution to the protected regions of the Ionian Archipelago and discusses the factors influencing the transport of MPs over the course of 27 months.

## 3. Materials and methods

### 3.1. Study area

The Ionian Archipelago (36°30’−40°N, 18°30’−21°30’E) is located west of mainland Greece, contains several islands, and according to the 2011 Population and Housing Census, its coasts are populated by more than 1.400.000 permanent residents (ELSTAT, 2011). For the purposes of this study, the 6 most populated cities near the coast were selected as sources of microplastic pollution. These are the cities of Patra (≥300.000 residents), Corfu (≥100.000 residents), Zante (≥40.000 residents), Igoumenitsa (≥25.000 residents), Lefkada (≥22.000 residents), and Argostoli (≥13.000 residents) (ELSTAT, 2011). Moreover, the Ionian Islands are among the most important touristic destinations in Europe, receiving more than 3 million visitors from major European countries in 2019 and 2020 (Statista, 2021).

The surface current dynamics of the Ionian Archipelago are mainly controlled by the prevailing water flow from the Aegean Sea. Surface water exits the Aegean Sea through the western Cretan Straits, and follows a northward flow along the coasts (Kalimeris and Kassis, 2020; Macias et al., 2019). The sea surface currents move among the Ionian islands, toward the Adriatic Sea (Fig. 1).

### 3.2. Particle-tracking model

TrackMPD is a particle-tracking numerical model that simulates the surface transport of marine plastic debris in the marine environment (Jalón-Rojas et al., 2019). In the present study, this model was adopted to simulate the transport of microplastic particles released at different locations. Besides the Lagrangian modeling of advection-diffusion, the model also incorporates the beaching behavior of particles, which is highly significant for the selected region due to the presence of islands very close to the mainland. The model's inputs consist of the initial particles' location (longitude, latitude, and depth), the study domain (longitude and latitude of the coastline), and a set of oceanographic data.

### 3.3. Oceanographic data

TrackMPD requires a set of oceanographic parameters that contain the hydrodynamic information of the simulated region. More specifically, a file was created containing the following parameters: horizontal current velocity ($u$) in the longitude direction in m/s, horizontal current velocity ($v$) in the latitude direction in m/s, water elevation ($E$) in m, and the time stamps associated with these parameters. The oceanographic data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS). More precisely, the authors extracted the Mediterranean Sea Analysis Forecast Physics (Clementi et al., 2021), which is supplied by the Nucleous for European Modeling of the Ocean

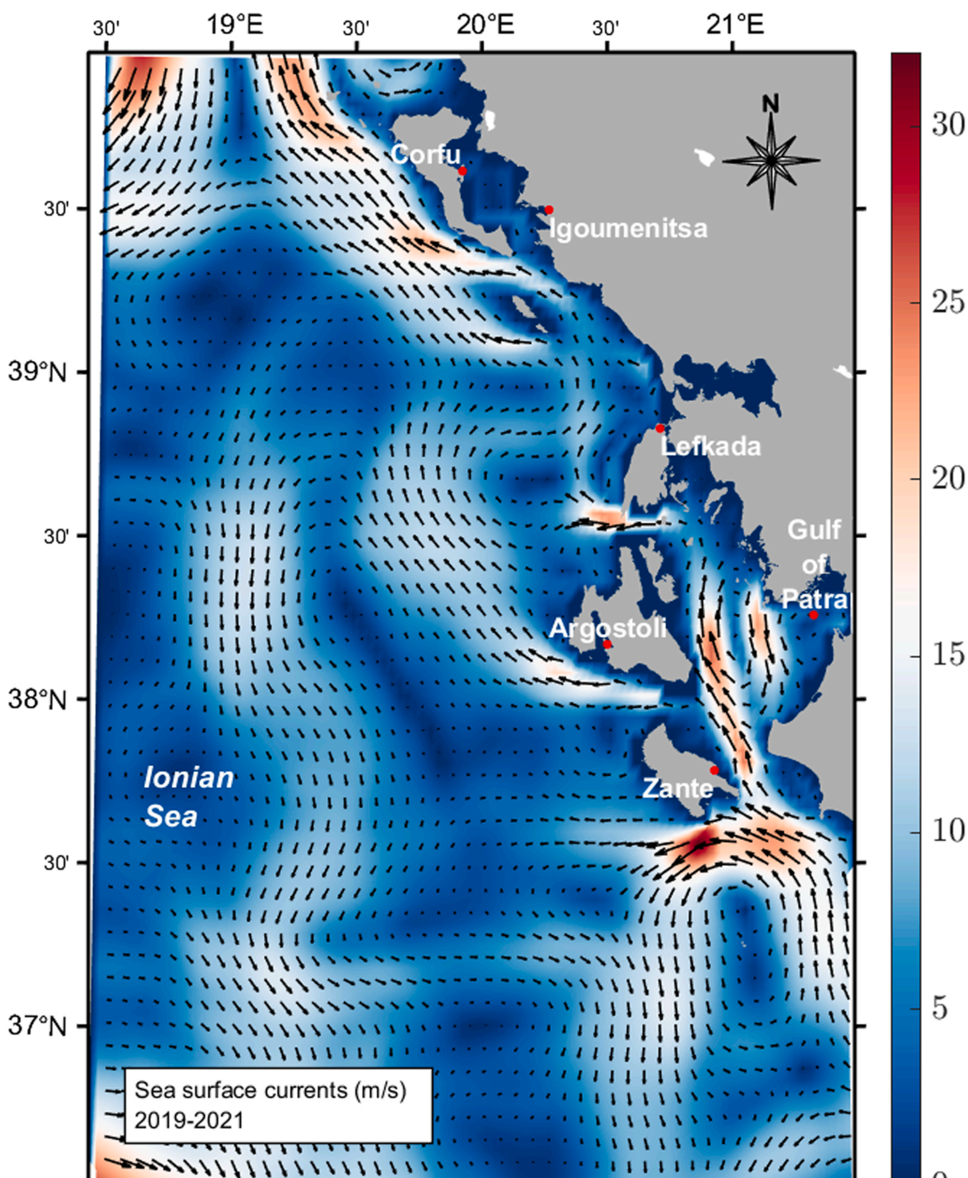


**Fig. 1.** Average sea surface currents (m/s) in the Ionian Archipelago and the MP particles release locations.

model (NEMO) for the period May 2019-August 2021.

### 3.4. General equations – Numerical solution

The particle tracking procedure was as follows. Particles initiate their trajectories from a standard released point and their coordinates are tracked after each time step, which in this experiment is 1 h. The particle's location in the spatial and temporal dimensions is governed by the advective and diffusive displacements according to the general equations (Jalón-Rojas et al., 2019):

$$\frac{dx}{dt} = \frac{dx_{adv}}{dt} + \frac{dx_{diff}}{dt} = \frac{u(x,y,t)}{dt} + \frac{dx'}{dt} \quad (1)$$

$$\frac{dy}{dt} = \frac{dy_{adv}}{dt} + \frac{dy_{diff}}{dt} = \frac{v(x,y,t)}{dt} + \frac{dy'}{dt} \quad (2)$$

where $dx_{adv}$ and $dy_{adv}$ are the advective displacement given by the horizontal velocity fields $u$ and $v$, and $dx_{diff}$ and $dy_{diff}$ are the diffusive displacement given by the random components $dx'$ and $dy'$ representing the turbulent diffusion that occurs at the particle's motion.

The numerical solution to the general equations (Eqs.:1,2) is as follows. The advective displacement of the particles' movement is calculated using a Runge-Kutta scheme of order 4/5, providing the current velocities in m/s. Then, the current velocities are multiplied by the duration between time steps ($\Delta t$) to calculate the particles' displacement in each component's direction. The diffusive displacement of the particles' movement is calculated using a random walk model to estimate the turbulent motion of particles in each component direction. The advective and diffusive displacements are then added to the particle's location in order to calculate its new location. Thus, Eqs. 1,2 are as follows (Jalón-Rojas et al., 2019):

$$x_{t+\Delta t} = x_t + u\Delta t + R\sqrt{2K_h\Delta t} \quad (3)$$

$$y_{t+\Delta t} = y_t + v\Delta t + R\sqrt{2K_h\Delta t} \quad (4)$$

where R ($\overline{R}$=0, $\sigma = 1$) is a random number generated at each time step and $K_h$ is the diffusion coefficient in $m^2/s$. The last part of equations 3,4 is the incorporation of the stochastic motion due to the turbulent diffusion, to the particles' motion. The diffusion coefficient $K_h$ is unknown and depends on the study site (Critchell and Lambrechts, 2016). In some studies, the diffusion coefficient is estimated as a function of the grid's resolution (Schönfeld, 1995; Neumann et al., 2014). In this study, this technique would suggest using a diffusion coefficient lower than 4 $m^2/s$. However, Cheng et al. (2020); Jalón-Rojas et al., (2019) showed that differences in the particles' motion with the use of diffusion coefficients between 1 and 5 $m^2/s$ are negligible. Therefore, this study assumes isotropic horizontal diffusivity keeping the reference diffusion coefficient of 1 $m^2/s$.

### 3.5. MP particles release experiment

In the marine area of each one of the selected cities, 100 MP particles were released on the 5th of May 2019 at 00:30 h and their displacements were estimated hourly until the 28th of August 2021 at 23:30 h. The basis for a time design of $\geq 2$ years is to investigate the physical processes with two complete annual cycles, let MPs agglomerate in specific patterns, and make sure beaching is significant. In terms of the microplastic properties, the polymer's density was 0.9 $g/cm^3$, which corresponds to polyethylene (PE) and/or polypropylene (PP) particles (Hidalgo-Ruz et al., 2012). Since we only simulate surface transport, the size and shape of microplastics were not included. This experiment tracks the fate of MP particles originating from major sources, and the influence of the surface circulation on the MP particle trajectory. Also, an analysis of the seasonal displacement magnitude in the years, will show the effect of climatic conditions on the distribution of floating MPs within the Ionian Archipelago region. The main interest is to investigate whether MP pollution originating from the major cities of the Ionian region can be a potential threat to every habitat and marine region of the Ionian Archipelago. The release locations of MP particles were selected to be at the marine area near the cities ($\leq$5 km), approximately where the urban wastewater treatment plants' (WWTPs) underwater pipes release the cities' sewage into the sea. Due to several challenges in terms of the environmental impacts and the design of WWTPs in Greece, the effluent from WWTPs is considered by this study as a direct source of MPs to the sea (Prochaska and Zouboulis, 2020). The release location named "Gulf of Patra" is not located inside the gulf of Patra but at its boundaries, where the surface water masses from the gulf of Patra flow into the open sea (Fourniotis and Horsch, 2015) Table 1.

### 3.6. Limitations of the present study

In the methodology described above, the authors simulate the transport of floating microplastic particles in the Ionian Archipelago using Lagrangian modeling. It should be noted that, some processes related to the particles' behavior in the marine environment (degradation, biofouling, sinking and deposition) are not considered in this study.

## 4. Results and discussion

### 4.1. MP pathways and fate

In this study, the authors used a numerical particle-tracking model to simulate the transport of MPs released from 6 sites within the Ionian Archipelago. The 100 particles released at each location were left drifting at sea for a period of 27 months and were subject to the influence of advection and diffusion. The pathways of MPs varied among sites. Also, MPs released from the same location exhibited different trajectories (Fig. 2). After the interval of 27 months, MPs were found either still drifting at sea or grounded at a nearby coastal location (Fig. 3).

### 4.2. MPs beaching characteristics

Beaching is one of the most significant processes for marine microplastic pollution since it determines the concentration levels of MP loads in the marine and coastal environment. At the end of the simulation experiment, the fate of approximately 63% of the released MPs was ending up on the coast (at a distance between 0 and 35 km from the release location), while the remaining 37% were still floating in the sea (at a distance between 0 and 60 km from the release location) (Figs. 3,4). Hence, floating MPs released within the Ionian Archipelago are most likely to end up off the region's coastline. MP pollution from Corfu poses a threat mostly to the coastal area south of the release location, with beaching sites ranging at a distance between 2 and 25 km. Igoumenitsa's MP loads reach nearby north coasts at a distance that does not exceed 10 km while most of the MP waste ended up beached at a location south of the release site at a distance between 0 and 32 km. The released MPs from Argostoli ended up beached north and south of the release location at a distance up to 13 km. The Lefkada's MP loads were also beached both north and south of the release site with most MPs following a southward trajectory and distances not exceeding 14 km. The Gulf of Patra was the only release location that did not exhibit beached particles north of it and showed the smallest extent of distances. Zantes' beached MPs were found both north and south of the release location with distances between 0 and 18 km in the north and 0 and 7 km in the south of the release location (Fig. 4).

Beaching time histograms better reveal this process within the Ionian Archipelago region. The shape of the histograms varies among different release locations showing a sensitivity of the MP beaching process to the source location (Fig. 5). All data sets were subject to statistical tests (Kolomogorov-Smirnov, Lilliefors, Chi-Square GoF) to identify the

**Table 1**
Comparison of studies on Lagrangian modeling of floating plastic debris in the marine environment.

| Study area | Horizontal resolution (km) | Number of particles | Release | Beaching | Integration time | Reference |
|---|---|---|---|---|---|---|
| Ionian Archipelago | 3 | 100 | Instantaneous | Yes | 27 months | Present study |
| North Pacific | 111 | 50 | Instantaneous | No | 5 years | (Kubota, 1994) |
| South Pacific | 111 | Not specified | Instantaneous | No | 8 years | (Martinez et al., 2009) |
| East China Sea | 9 | 20,000 | Instantaneous | Yes | 76 days | (Isobe et al., 2009) |
| Japan Sea | 18 | 47,676/y | Monthly | Yes | 4 years | (Yoon et al., 2010) |
| Mediterranean Sea | 14 | 400,000/w | Weekly | No | 28 days | (Pizzigalli et al., 2007) |
| Global Ocean | 55 | Not specified | Instantaneous | Yes | 10 years | (Maximenko et al., 2012) |
| Global Ocean | 111 | Not specified | 6/y | No | 1000 years | (Van Sebille et al., 2012) |
| Global Ocean | 20 | $9.6x10^6$ | 1/y | Yes | 30 years | (Lebreton et al., 2012) |
| Southern North Sea | 10 | 200 | 1/28 h | No | 90 days | (Neumann et al., 2014) |
| Mediterranean Sea | 10 | 3287 | Daily | Yes | 1.3 years | (Mansui et al., 2015) |
| Adriatic Sea | 2.2 | $6x10^{10}$ | 1/10 d | Yes | 6 years | (Liubartseva et al., 2016) |
| Mediterranean Sea | 7 | $10^9$/y | Daily | Yes | 4.5 years | (Liubartseva et al., 2018) |
| Adriatic Sea | 2 | 9398 | Instantaneous | Yes | 60 days | (Carlson et al., 2017) |
| W Mediterranean Sea | 12 | 1000 | Instantaneous | No | 50 days | (Aliani and Molcard, 2003) |
| Mediterranean Sea | 55 | Not specified | Instantaneous | No | 10 years | (Zambianchi et al., 2017) |
| NW Mediterranean Sea | 2 | Not specified | Biweekly | No | 30 days | (Fossi et al., 2017) |
| Aegean Sea | 7.5 | $10^4$/y | Monthly | Yes | 1 year | (Politikos et al., 2017) |

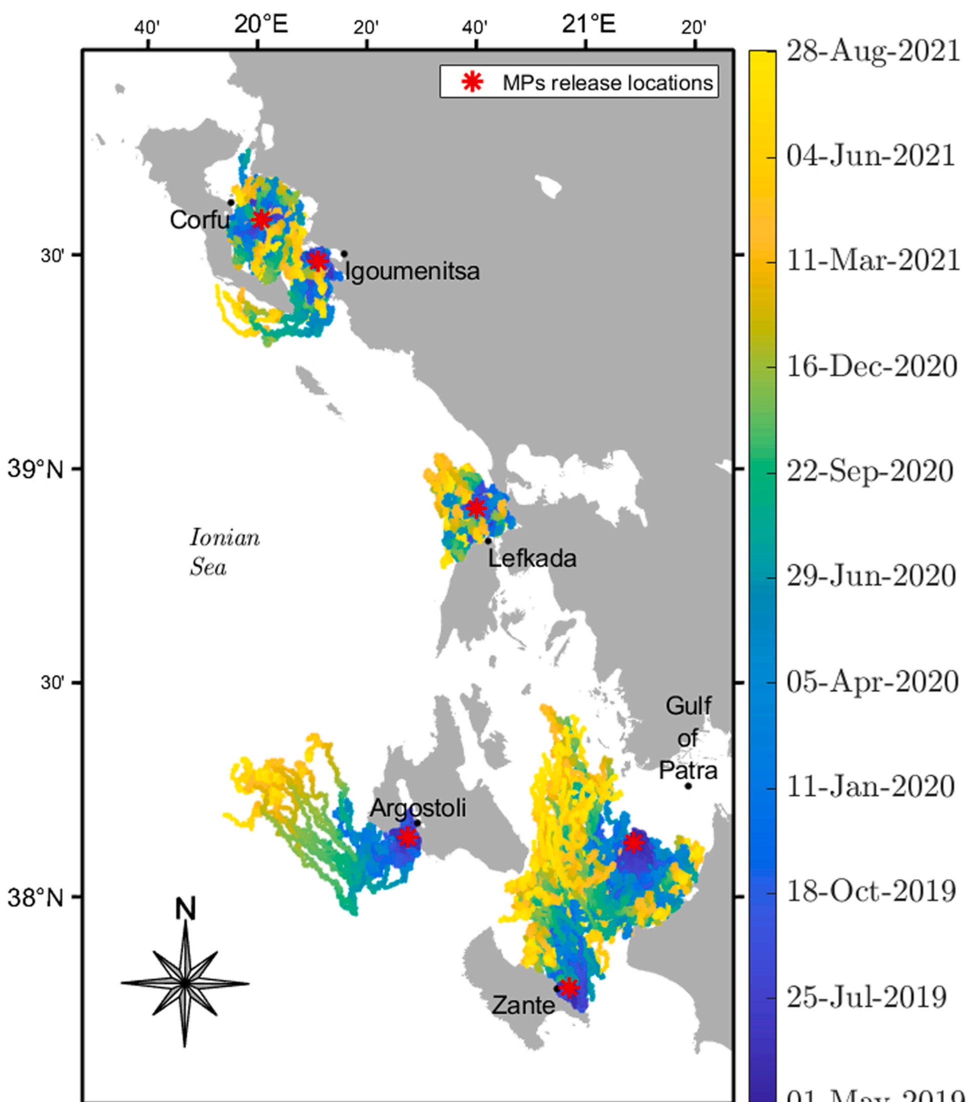


**Fig. 2.** Pathways of MPs during the simulation period.

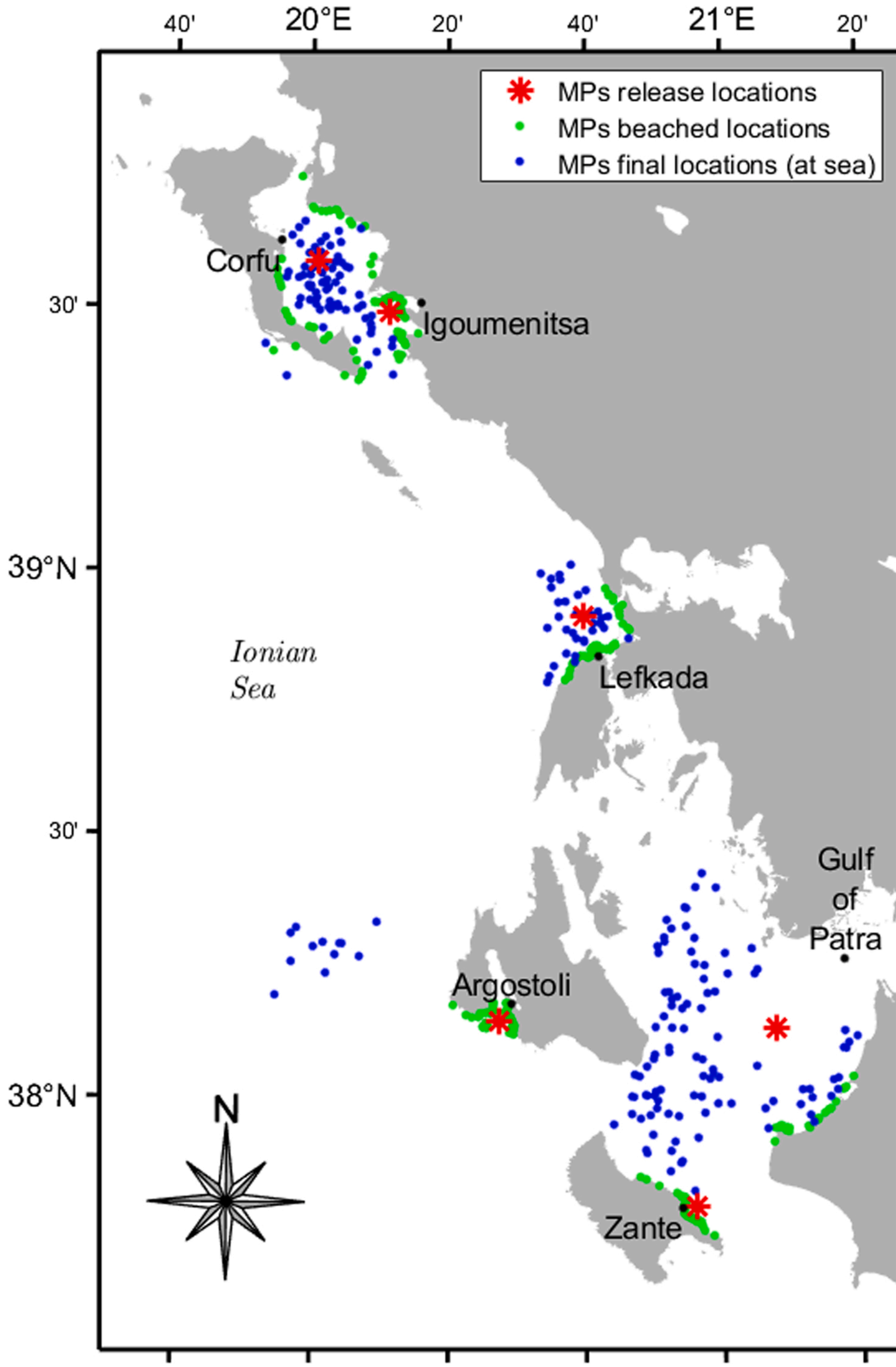


**Fig. 3.** Final location of MPs after the simulation period.

distribution type of the beached MPs from each release location. The analysis showed that the beached MPs from Corfu and the Gulf of Patra follow normal distributions, from Igoumenitsa, Zante, and Argostoli follow exponential distributions and from Lefkada follow the poisson distribution. Based on the distributions of the data, the probability density function (PDF) of beaching at time *t* was fitted on each histogram. In the cases of Igoumenitsa, Argostoli, and Zante, MPs tended to ground early after being released. In Igoumenitsa more than 30 MPs were grounded in the first 3 months of the simulation (not shown due to the selected bin width of the histograms) with the time to first grounding being 17 days. In Argostoli, the beaching times were shorter with more than 40 MPs grounded in the first 3 months of the simulation. However, the time to first grounding was higher (28 days). Zante showed the earliest time to first grounding (16 days), with more than 25 MPs grounded in the first 3 months of the simulation. The beaching times of MPs released from Lefkada followed a poisson distribution with small numbers of particles grounded in the first 6 months of the simulation ($\leq$10 MPs), followed by the highest numbers of grounded MPs in the next 6 months (25 MPs) that steadily decay until the end of the simulation. The time to first grounding was 85 days. The cases of Corfu and the gulf of Patra exhibited the longest times to first grounding of 226 and 341 days, respectively. Here, MPs stayed at sea for longer times and

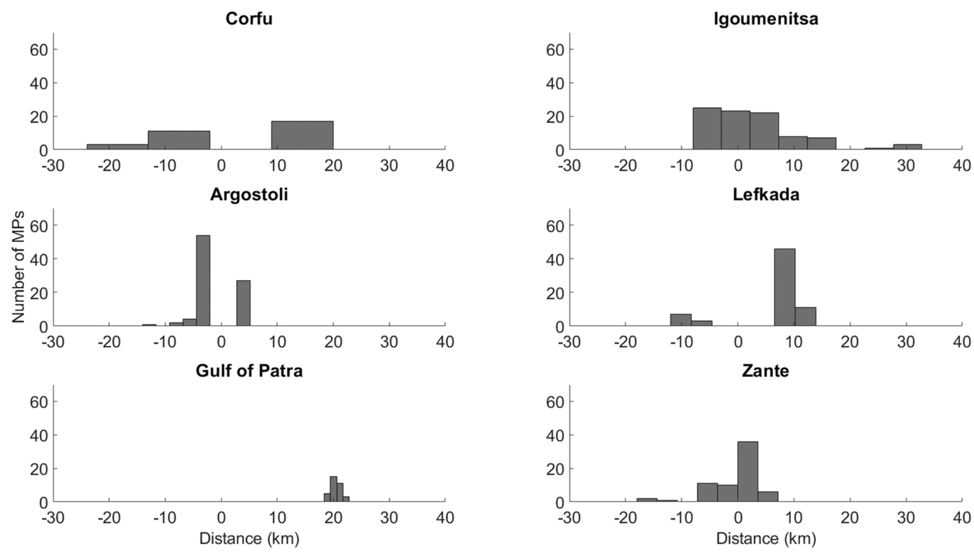


**Fig. 4.** Distribution of beached MPs in the surrounding areas of the release locations (with negative values implying northward and positive values southward displacements).

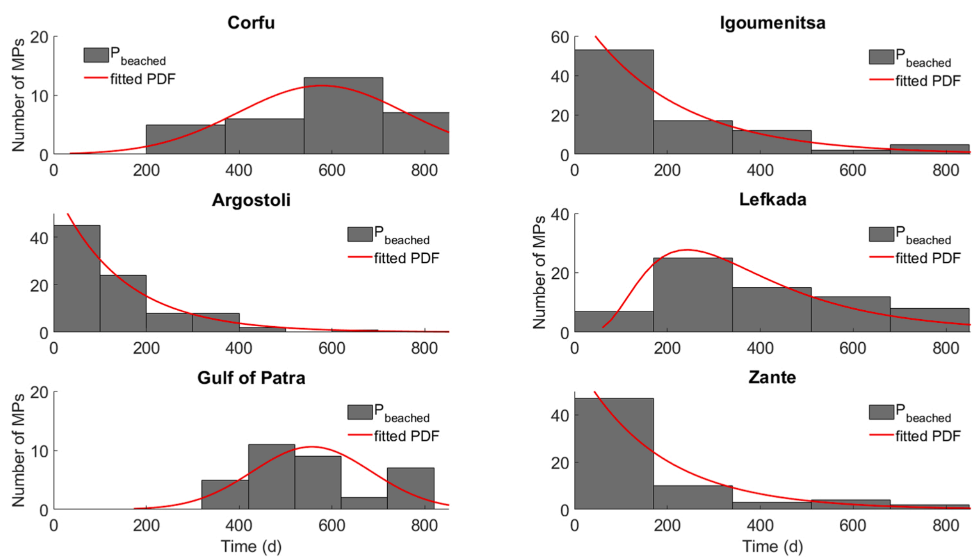


**Fig. 5.** Temporal beaching scales and probability density functions of MPs from each release location.

showed the highest numbers of beached particles after approximately 20 and 15 months, respectively.

### 4.3. Dispersion of MPs in the Ionian Archipelago

The behavior of MPs from each release location exhibits different patterns, with a number of particles moving away at great distances while most of the particles follow circular motions, and end up at sea or the coast not far away from the release location (see Figs. 2,3). Thus, investigating the dispersion of MPs is essential to understand the forces that control the movement of MPs within the Ionian Archipelago.

As explained by Pawlowicz et al. (2019), the typical approach for investigating the dispersion in the open ocean (Davis, 1991; LaCasce, 2008) cannot be applied to the topography of a marine area similar to the Ionian Archipelago. Instead, following an approach (commonly used in estuaries) that compares seaward transport $U$ and eddy diffusivity $A$ as separate phenomenological parameters is more appropriate (Fischer et al., 1979; Chatwin and Allen, 1985; Pawlowicz et al., 2019). Although this approach is not valid for all motives, it can be helpful for understanding latitudinal dispersion.

The approach used to understand the effect of seaward transport and eddy diffusivity on the dispersion of MPs along the Ionian Archipelago is the one used by Pawlowicz et al. (2019) who studied the dispersion of drifters in the Strait of Georgia (British Columbia, Canada) and is as following:

MP particles are being inserted at a fixed location ($x = 0$), and at a rate $D$ per unit of time, on the surface of a 1-D setting simulating the study area. The particles are exiting the setting at a time $\alpha^{-1}$ emerging from the beaching time of MPs. The movement of particles is controlled by two forces, the seaward transport ($U \geq 0$) and eddy diffusivity $A$, assumed constant at $x = 0$. Therefore, the concentrations of MP particles at each point and time $C(x, t)$ are expressed by the following equation:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = A\frac{\partial^2 C}{\partial x^2} - \alpha C + D\delta(x) \quad (5)$$

where $\delta$ is the Dirac delta function. The steady state solution to Eq. 5 is the following:

$$C(x) \Rightarrow \begin{cases} C_0 e^{\frac{-|x|}{L_N}}, & \text{for} \quad x < 0. \\ C_0 e^{\frac{-|x|}{L_S}}, & \text{for} \quad x > 0. \end{cases} \tag{6}$$

where:

$$L_N = \frac{2}{\frac{U}{A} + \sqrt{\left(\frac{U}{A}\right)^2 + 4\frac{\alpha}{A}}} \tag{7}$$

$$L_S = \frac{2}{-\frac{U}{A} + \sqrt{\left(\frac{U}{A}\right)^2 + 4\frac{\alpha}{A}}} \tag{8}$$

with a maximum of:

$$C_0 = \frac{\frac{D}{\alpha}}{L_N + L_S} \tag{9}$$

where $L_N$ and $L_S$ are the mean displacements of MP particles north and south of the release location respectively. Their magnitude depends on the effect of $U$ and $A$, and the relationship is given by the following equations:

$$U = \alpha(L_S - L_N), \qquad A = \alpha L_N L_S \tag{10}$$

From Eqs. 7,8 it becomes clear that the two scales controlling the displacement of particles are the advective/diffusive balance ($A/U$) and the diffusive/beaching balance ($\sqrt{A/\alpha}$). For $A/U \gg \sqrt{A/\alpha}$ (i.e. in the case of weak advection and/or short beaching times of MPs), MPs exhibit symmetric distributions with $L_N \approx L_S \approx \sqrt{A/\alpha}$ This behavior is observed in the distributions of MPs released from Corfu and Lefkada (Figs. 2,3,6). While for $A/U \ll \sqrt{A/\alpha}$ (i.e., in the case of large advection and/or long beaching times of MPs), MPs exhibit asymmetric distributions with $L_N \approx A/U$ and $L_S \Rightarrow \infty$. This behavior is observed in the distributions of MPs released from Igoumenitsa, Zante, Argostoli, and the gulf of Patra (Figs. 2,3 and 6).

As shown by Eq. 6, the concentration of MPs should decrease exponentially on both sides of each release location. However, there are some features in the observed distribution of MPs that do not follow this pattern. In the northward displacements of MPs released from Argostoli and the gulf of Patra, secondary peaks are observed at a distance of 45 and 20 km approximately (Fig. 6). These peaks emerge from circular motions of the particles at about this distance from the release location. This phenomenon adds a positive bias to the $L_N$ of these locations, which reaches higher values. Also, in the northward displacements of MPs released from Corfu, and the southward displacements from Corfu, Lefkada, and the gulf of Patra, the concentration of MP particles does not decrease immediately upon release, but rather remains stable for some time with small fluctuations. In the case of Corfu this phenomenon could be explained by the enclosed character of the gulf that is subject to weak advection, while in the cases of Lefkada and the gulf of Patra this may be related to circular rotations of particles (Fig. 1).

Nevertheless, following this approach it is observed that $L_N \approx L_S$ for distributions of MP particles released from Corfu, Lefkada, and the gulf of Patra, while for Argostoli and Zante the northward mean displacement is 2.7 and 5.8 times higher than the southward mean displacement respectively, and for Igoumenitsa the $L_S$ is 4.5 times higher than $L_N$ (Fig. 6). Moreover, the seaward transport $U$ and the diffusivity $A$ were estimated using equation 10. By comparing these two forces that mainly control the dispersion of MPs within the Ionian Archipelago, it is observed that diffusion is the primary force controlling the movement of MP particles in the regions of Corfu and Lefkada, while in the other regions, both advection and diffusion influence their displacements (Fig. 6).

### 4.4. Implications of floating MPs in the Ionian Archipelago

To the authors' knowledge, there are four studies with sampling of floating MPs within the Ionian Archipelago. In the study of Adamopoulou et al. (2021), two sampling campaigns occurred in the Corfu gulf with a total of six sampling stations. Their study showed higher concentrations of floating MPs within the Corfu gulf (type: fragments) than the Saronikos gulf in Athens (Greece), reaching up to 1 particle/$m^2$, and an effect of local surface oceanographic conditions (slicks) that concentrate higher numbers of MPs. The accumulation of MP particles on slicks poses a threat to biodiversity since they are known as nursery habitats for oceanic fauna from zooplankton to fish larvae (Whitney et al., 2021; Jillett and Zeldis, 1985; Weidberg et al., 2014). More specifically, in the marine region of the Corfu gulf, a study of MPs in mussels

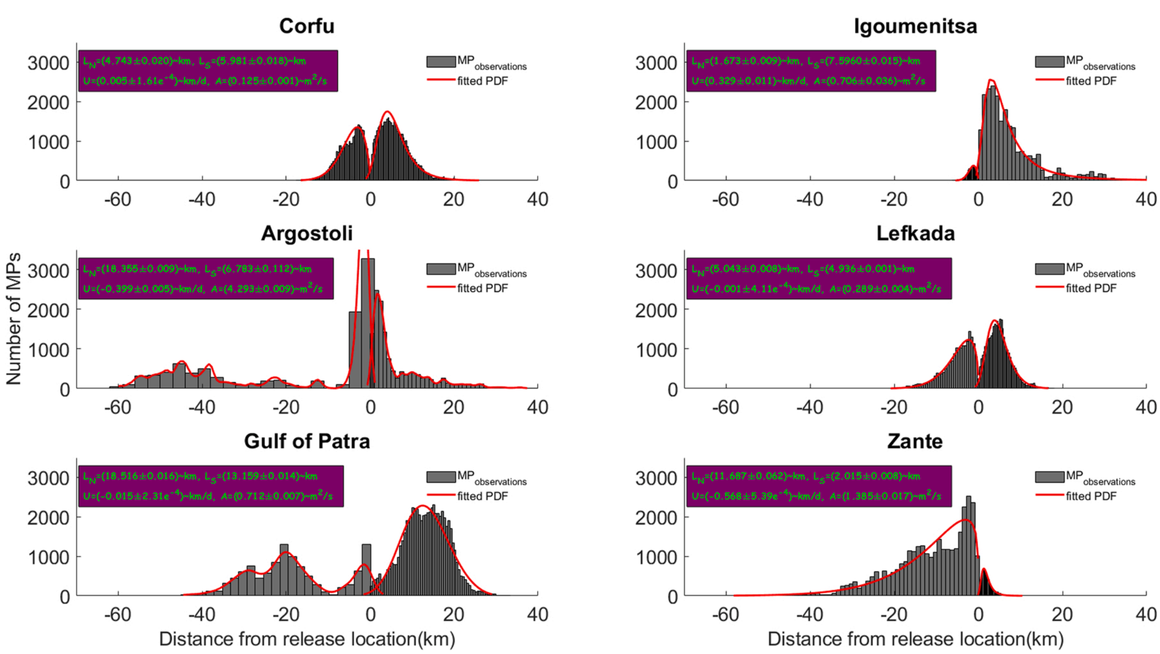


**Fig. 6.** One-dimensional displacements of MPs by distance from the release locations (with negative values implying northward and positive values southward displacements). The mean displacements in each direction $L_N$ and $L_S$ are shown, as well as the seaward transport $U$ and the diffusivity $A$ for each release location, estimated using equation 10. The standard errors for each parameter were estimated using the bootstrap estimation method (Efron and Tibshirani, 1994).

and fish showed an abundance of 1–2 MP particles per individual (Digka et al., 2018).

In the study of Ruiz-Orejón et al. (2016), the authors sampled floating MPs in various locations within the Ionian Archipelago, and found maximum abundances in their sampling stations north of Lefkada (1.16 particles/$m^2$), and minimum in the northeast of Zante (0.009 particles/$m^2$). Another study that sampled floating MPs within various areas of the Adriatic Sea, exhibited the highest concentrations of floating MPs (1.3 particles/$m^2$) in the gulf of Corfu between Corfu and Igoumenitsa (Zeri et al., 2018). Also, in the study of Kedzierski et al. (2022), a sampling station between the islands of Kefalonia and Zante showed low concentrations of floating MPs ((0.003 particles/$m^2$)). The results of these studies are in agreement with the results of this study regarding the main factors controlling the transport of floating MPs within the Ionian Archipelago. In regions where diffusion influences transport more than advection, accumulation of MPs has been reported in the previously mentioned studies. Instead, the same studies report minimum concentration of floating MPs in areas where advection is the main force affecting transport.

There is a number of studies that have investigated marine debris accumulation areas in the Mediterranean Sea (Liubartseva et al., 2016; Mansui et al., 2015; Politikos et al., 2017). In the study of Liubartseva et al. (2016), the Corfu gulf is found to maintain most marine debris distributed to the marine environment by its coasts. Their findings agree with the result of this study's simulation experiment, where it is observed that after 27 months MPs released in the Corfu gulf are either still drifting or grounded at the gulf's coasts. Only in the case of MPs being released from Igoumenitsa it was noticed that a small fraction of particles passed south of the southeast coast of Corfu and was drifted to the west coast of the island (Figs. 2,3). In the study of Mansui et al. (2015) the authors determined the receptors of floating marine debris within the Mediterranean Sea. The results of their study show that the Ionian Archipelago is not an accumulation area affected by the MP abundance of the Mediterranean Sea, but rather affected only by local sources with MPs exhibiting smaller velocities compared to other Mediterranean areas. Therefore, residence times of floating MP particles released from the locations selected by the present study are important to determine whether their concentrations could be subject to sinking and deposition processes, and the risks of MP accumulation in a specific region.

The majority of floating MPs at sea are known to be removed within 2 years by biological processes (Kvale et al., 2020a). However, studies have shown that floating MPs on the surface of the sea are increasing, implying the existence of a transport cycle of MPs at sea (Kvale et al., 2020b; Wilcox et al., 2019). MPs within the Ionian Archipelago either remained at sea after the 27 months simulation, or were grounded at the local coasts. Therefore, their transport and beaching behavior as well as residence times, are used to determine the threat level that MPs released from each location pose to the local biodiversity. The transport of MPs within the Corfu gulf is characterized by small movements with 31% of the released particles beached within the interval of the 27 months (Figs. 2 and 3). Considering that the first grounding did not occur until after 226 days, this region is characterized by long residence times and therefore MPs can pose a threat to local biodiversity as they will either remain at the surface where they could be ingested by the marine fauna, or they will eventually sink and accumulate in the region's bottom habitats. Similarities to Corfu are observed in the gulf of Patra. Here, MP transport is characterized by larger movements but again with small numbers of beached particles (34 %) (Figs. 2 and 3). Taking into account that in the gulf of Patra the longest time to first grounding was estimated (341 days), the region is subject to long residence times and MPs may pose a threat to the local habitats. In Argostoli, the majority of the released particles exhibited small movements and high beaching probability, with 88 % of particles beached within the simulation period and time to first grounding is 29 days. The remaining 12 % escaped the coastline of the island of Kefalonia and followed the region's surface currents (Fig. 1) were transported away from the release location toward the open sea (Figs. 2 and 3). Thus, the fate of MPs in Argostoli is subject to short residence times, with a high probability of grounding within the first weeks upon being released (Fig. 5). In Igoumenitsa and Zante the shortest times to first beaching were observed (18,17 days respectively). Igoumenitsa showed small movements of particles with the highest numbers of beached MPs among all release locations (89 %), and a small fraction of particles transported to long distances toward the west coast of Corfu island (Figs. 2 and 3). Zante, on the other hand, showed slightly larger movements with moderate numbers of beached particles (66 %). In both cases, MPs tend to either beach in short times or be transported away from the released location, resulting in short residence times. Lastly, Lefkada exhibited small movements in scales similar to Corfu and a moderate number of beached particles (67%) and time to first grounding (86 days) (Figs. 2 and 3). Considering that the beaching probability shows a peak after the first 6 months of the simulation, and that particles do not move far from the release location, the region can be characterized as moderate in terms of residence times and with a moderate risk to the local biodiversity.

## 5. Conclusions

In this study, the authors present the first results on the transport of MPs originating from major sources within the Ionian Archipelago. The findings report a high risk of local biodiversity in the areas of Corfu and the gulf of Patra, moderate risk of Lefkada, and a small risk of Zante, Igoumenitsa, and Argostoli. The transport of MPs is mainly controlled by diffusion in the areas of Corfu and Lefkada, while both advection and diffusion influence the particles' displacements at Igoumenitsa, Zante, Argostoli, and the gulf of Patra. Beaching occurred rapidly for MPs released from Igoumenitsa, Argostoli, and Zante, while Corfu and the gulf of Patra exhibited long beaching times. Lefkada's beaching times were found to be in the middle of all stations. Overall, the dispersion of MPs was found to affect mostly the nearby coastal areas at distances that reach no further than 35 km away. The MPs that were still floating at the end of the simulation were not transported further than 60 km from the release location. Therefore, the MP pollution originating within the Ionian Archipelago affects the marine ecosystem of the same region, and considering the highly touristic character of the Ionian Islands, this could cause serious problems to a great number of marine species and protected areas. In the future, the authors would recommend the organization of a sampling campaign that will scrutinize the Ionian Archipelago with multiple net tows in order to present a more detailed report of the problem.

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## CRediT authorship contribution statement

**Simantiris Nikolaos:** Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft preparation, Visualization. **Theocharis Alexandros:** Visualization, Methodology, Validation, Writing – reviewing and editing. **Avlonitis Markos:** Supervision, Writing – review and editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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