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ARTICLE

Evaluating Microplastic Concentrations in the Al Hoceima Marine Protected Area: Implications for Identifying Pollution Hotspots and Formulating Conservation Strategies

Hasna Bouazzati [1*] , ***Asma Damghi*** [1] , ***Abdelmounim El M'rini*** [1] , ***Souhail Karim*** [2] , ***Mohamed Maanan*** [3]

[1] *Research Laboratory in Applied and Marine Geosciences, Geotechnics and Geohazards (LR3G), Faculty of Sciences, Abdelmalek Essaadi University, Tetouan 93000, Morocco*

[2] *Research Laboratory in Applied and Marine Geosciences Research and Development, Faculty of Sciences and Techniques, Abdelmalek Essaadi University, Al Hoceima 32000, Morocco*

[3] *Laboratory LETG UMR 6554 CNRS, Institute of Geography and Planning, Nantes University, Nantes 44035, France*

ABSTRACT

Global marine ecosystems are significantly endangered by microplastic pollution, leading to comprehensive investigations into its distribution and impacts on the health of ecosystem. This research employs the Alseamar Autonomous Underwater Vehicle (AUV) known as Glider to investigate microplastic concentrations within the Al Hoceima Marine Protected Area (MPA). Our objective is to identify spatial patterns that reveal pollution hotspots and furnish data for targeted conservation efforts and pollution prevention. We aim to identify regions with elevated microplastic concentrations by meticulously analyzing microplastic level graphs, with a specific focus on temporal variations. The results reveal notable patterns, such as increased densities around fishing harbors and near urban centers, potentially linked to anthropogenic activities. Additionally, we observe variations in pollution levels throughout different glider operation cycles, underscoring the importance of understanding the spatio-temporal

*CORRESPONDING AUTHOR:
Hasna Bouazzati, Research Laboratory in Applied and Marine Geosciences, Geotechnics and Geohazards (LR3G), Faculty of Sciences, Abdelmalek Essaadi University, Tetouan 93000, Morocco; Email: bouazzati.hasna@gmail.com

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dynamics of microplastic distribution. Al Hoceima Marine protected areas exhibiting lower microplastic concentrations illustrate the efficacy of such zones in alleviating pollution impacts, thereby underscoring the significance of conservation efforts in safeguarding marine biodiversity and ecosystem resilience. Ultimately, our research enhances our comprehension of the pressures exerted by humans on marine environments and underscores the necessity of proactive conservation measures to shield marine ecosystems from the threats posed by microplastic pollution.

Keywords: Microplastics; Marine Protected Area; Al Hoceima; Gliders; Pollution Hotspots; Conservation Strategies

1. Introduction

Plastic pollution is an escalating global concern due to its persistent nature and detrimental impact on marine ecosystems [1, 2]. Since the onset of large-scale manufacturing, global plastic production has increased more than twentyfold [3]. Despite various initiatives aimed at reducing or eliminating plastic waste, plastic pollution in marine environments continues to rise [2–4]. By 2050, it is projected that over 12 billion metric tons of plastic waste will be produced, a significant proportion of which will remain unmanaged and eventually enter the oceans [5, 6].

Once introduced into marine systems, plastic debris persists and gradually fragments into microplastics—defined as plastic particles smaller than 5 mm in size [7]. These microplastics have become ubiquitous in marine environments, with studies identifying numerous global pollution hotspots. For instance, research conducted along the Hong Kong coastline revealed substantial microplastic presence on 25 beaches, with over 90% of collected debris consisting of microplastic particles [8]. Similar findings were reported in ten estuaries in northwest England [9] and in the Scilly Islands, United Kingdom, where concentrations reached up to 517,000 particles per square meter and over 700 particles per kilogram of dry sediment [10]. Additionally, the Ebro River contributes an estimated 2.14×10^9 microplastics to the Mediterranean Sea annually [11], while elevated concentrations have also been recorded in various African coastal waters [12–14].

Microplastics are particularly concerning due to their longevity and ability to adsorb toxic pollutants such as heavy metals, persistent organic pollutants (POPs), and hydrocarbons [15]. These pollutants may originate from primary sources (e.g., microbeads and industrial pellets) or secondary sources (fragmentation of larger plastics) [16]. Plastics are manufactured through polymerization processes involving monomers like ethylene, which forms polyethylene (used in plastic bags), vinyl (polyvinyl chloride), styrene (polystyrene), and esters (polyesters), many of which exhibit varying chemical compositions and environmental toxicities.

The ecological implications of microplastics are profound. Numerous studies have demonstrated their adverse effects on marine biodiversity, including ingestion by marine organisms, bioaccumulation in food webs, and physical and chemical toxicity [7–17]. Furthermore, evaluating the risks associated with microplastics remains a scientific challenge due to limited qualitative and quantitative data on their concentrations, chemical profiles, and ecological impacts [17]. Beyond ecological harm, microplastics pose risks to human health and create aesthetic, economic, and management challenges in coastal and marine areas [18, 19].

Marine Protected Areas (MPAs) are key conservation tools designed to safeguard marine ecosystems, maintain biodiversity, and ensure the sustainable use of marine resources. However, the presence of microplastics within MPAs threatens these objectives by introducing long-lasting contaminants that can disrupt ecosystem functioning and harm marine life [20]. Assessing microplastic levels within MPAs is therefore crucial for understanding the scope of the problem and designing effective conservation and mitigation strategies [20].

Recent studies have shown that MPAs are not exempt from plastic pollution. Notably, in the Al Hoceima Marine Protected Area (MPA), significant concentrations of microplastics have been recorded. For example, microplastic levels in Al Hoceima Bay averaged 4.70 ± 4.50

items per m^3, with fibers and fragments identified as the dominant particle types [21]. These findings illustrate the growing challenge faced by MPAs in addressing microplastic contamination and highlight the urgent need for focused conservation measures targeting pollution hotspots [22].

Understanding the extent and ecological consequences of microplastic pollution is essential for enhancing marine conservation initiatives and developing effective management policies. Identifying spatial distribution patterns and high-concentration zones within MPAs will enable targeted interventions, support mitigation efforts, and contribute to sustainable ecosystem-based management [2–8].

2. Study Area

The Al Hoceima Marine Protected Area (MPA) is located on Morocco's Mediterranean coast and forms part of the Al Hoceima National Park, which includes both terrestrial and marine ecosystems. The national park covers a total area of approximately 48,460 hectares, with the marine component covering about 19,000 hectares. It includes a portion of the Alboran Sea, recognized for its unique oceanographic and biological characteristics [22]. The MPA safeguards diverse marine habitats, such as rocky reefs, seagrass meadows, and pelagic zones, all essential for the conservation of marine biodiversity. Additionally, our global research has underscored the significance of MPAs in mitigating the impacts of climate change, leading to the selection of the Al Hoceima MPA. The MPA's marine boundaries span from 35°13' N to 35°21' N latitude and from 3°51' W to 4°11' W longitude (**Figure 1**). These boundaries include both no-take zones and areas with regulated fishing activities to maintain ecological balance. Given its integration with the national park, the Al Hoceima MPA plays a vital role in connecting marine and terrestrial conservation efforts. This region encounters environmental challenges due to coastal development, fishing activities, and potential pollution sources, highlighting the importance of continuous monitoring and assessment to ensure effective conservation management [22, 23].

The Al Hoceima MPA holds ecological importance owing to its abundant biodiversity and the existence of numerous endangered and rare species. It includes various marine habitats, including coral reefs, seagrass beds, and rocky coasts, all of which serve as essential breeding and feeding grounds for numerous aquatic organisms. Maintaining the ecological integrity of the Al Hoceima MPA is crucial for sustaining marine biodiversity, supporting fisheries, and ensuring the long-term health of the marine ecosystem. Consequently, investigating microplastic pollution in this region is essential for improving conservation initiatives and safeguarding the ecological resilience of the Al Hoceima Marine Protected Area [24].

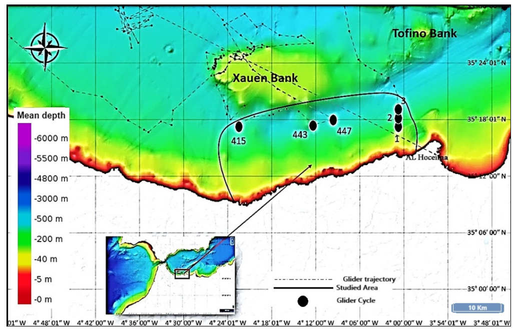


Figure 1. A map of the study area featuring a color-coded bathymetric profile that delineates the Marine Protected Area of Al Hoceima. The map emphasizes the primary glider mission route from the inaugural mission, encompassing cycles 1, 2, 3, 415, 443, and 447, executed under Project Odyssea.

3. Materials and Methods

3.1. Glider Missions

This study focuses on data collected during the first and second glider missions conducted by the Moroccan association AGIR (leader of the Marine Observatory of Al Hoceima) in the Western Alboran Sea, as part of the European ODYSSEA project [25]. The first expedition took place in late autumn 2020, from November 10th to December 11th [26], while the second mission was carried out between February 11 and March 23, 2021, covering the transition from winter to early spring.

During the first mission, a SeaExplorer glider—developed by ALSEAMAR (France) and equipped with a Seabird CTD—completed 873 vertical profiles (cycles) from the surface down to approximately 500 meters, at a sampling interval of 4 seconds [27].

3.2. Instrumentation and Data Collection

To evaluate water quality within the Al Hoceima Marine Protected Area (MPA), autonomous underwater vehicles (AUVs), specifically Alseamar SeaExplorer gliders, were deployed. These gliders were fitted with high-precision sensors, enabling the acquisition of real-time, in situ data that complement satellite and conventional maritime observations. The measured parameters included temperature, salinity, dissolved oxygen, chlorophyll-a concentration, and microplastic presence [27, 28].

The glider operated along a sawtooth trajectory, repeatedly descending and ascending through the water column. This motion enabled multi-depth sampling and produced a continuous vertical profile of the marine environment. Such profiling was essential to determine the vertical distribution of microplastics, as well as to identify depth-specific concentration gradients and potential accumulation zones. High-resolution bathymetric data were also generated during this process.

Microplastic detection was carried out using optical and fluorescent sensors installed on the glider. These sensors distinguished microplastic particles from other suspended materials based on unique visual signatures and spectral characteristics [28]. Upon surfacing, the glider connected to a satellite system, transmitting the collected data in near-real-time to the research team, thereby allowing for continuous monitoring and rapid preliminary analysis [29].

To ensure spatial representativeness, the gliders were strategically deployed across the Alboran Sea and within key sectors of the Al Hoceima MPA. From the 750 total usable glider cycles collected during the 32-day autumn mission, six adjacent transects near the MPA were selected for focused analysis: three in the eastern region, two in the central area, and one in the west. This distribution enabled the identification of potential pollution hotspots and provided robust spatial coverage of the study area.

3.3. Processing and Analysis of Collected Data

Following data acquisition, all datasets were processed and analyzed using the ODYSSEA integrated platform, which supports harmonized and scalable marine data workflows [22–25].

- Data Cleaning and Validation: Initial processing included removing sensor noise, correcting drift, and standardizing units. Quality control procedures followed ODYSSEA guidelines to ensure consistency. Blank samples and calibration protocols were also used to assess sensor performance and minimize measurement uncertainties, particularly for microplastic detection.
- Data Integration: Cleaned glider data were integrated with satellite-derived parameters (e.g., sea surface temperature, ocean color) and other auxiliary datasets. Spatial and temporal synchronization was applied to allow direct comparison and integration of heterogeneous data sources.
- Statistical Analysis: Descriptive statistics, spatial trend analysis, and correlation matrices were generated to explore patterns in the measured variables. Anomaly detection and outlier analysis helped in pinpointing regions with elevated microplastic concentrations, interpreted as potential pollution hotspots.
- Machine Learning Applications: Machine learning algorithms were applied to enhance pattern recognition and forecast spatial trends in microplastic distribution. Models were trained on merged datasets to predict areas of high contamination and assess relationships between microplastics and other water quality indicators.
- Adaptive Monitoring Framework: Throughout the study, iterative updates and parameter tuning were implemented to improve data robustness. This adaptive framework ensured reliable monitoring even under variable oceanographic conditions.

The ODYSSEA platform's capacity to manage large, multi-source datasets and support advanced analytics made it a valuable tool for improving data transparency, fostering stakeholder collaboration, and generating actionable insights to support marine conservation and pollution mitigation efforts [26, 27].

4. Results

4.1. Geospatial Distribution of Microplastics in the Al Hoceima Marine Protected Area

The microplastic dataset, obtained from the initial glider missions in the Al Hoceima Marine Protected Area (MPA), specifically from cycles 1, 2, 3, 415, 443, and 447, yielded valuable insights into the spatial and vertical distribution of microplastic pollution. These glider deployments, conducted as part of the ODYSSEA project, enabled continuous, high-resolution monitoring throughout the MPA and revealed several potential pollution hotspots.

Microplastic detection was carried out using onboard optical and fluorescence-based sensors. Two key parameters were used for this analysis: MPS_MP_COUNT (microplastic mass concentration) and MPS_PAR_COUNT (microplastic particle count). These variables served as the foundation for quantifying the abundance and estimated mass of microplastics within the water column.

MPS_MP_COUNT (**Figures 2** and **3**) measures the estimated mass of microplastics, expressed in micrograms per liter (μg L^{-1}) or milligrams per cubic meter (mg m^{-3}). Mass estimates provide further insight into the volume and potential toxicity of microplastics present in the water column. The highest recorded values were observed in surface layers in the eastern zone, with concentrations up to 1.85 mg m^{-3}, compared to 0.6–1.2 mg m^{-3} in the western transects.

MPS_PAR_COUNT (**Figures 4** and **5**) represents the number of detected microplastic particles per unit volume, typically expressed in particles per cubic meter (particles per m^3). In relatively clean marine environments, this value is often below 1 particle per L, while in more polluted waters, concentrations can exceed thousands of particles per liter, indicating severe contamination and potential ecological risk. In our study, particle counts in the eastern zone of the MPA reached up to 6.21 ± 2.3 items per m^3 in surface layers (0–5 m), declining with depth. In contrast, the central and western sectors showed lower concentrations, ranging from 1.9 ± 0.8 to 3.2 ± 1.1 items per m^3, depending on depth and sampling cycle.

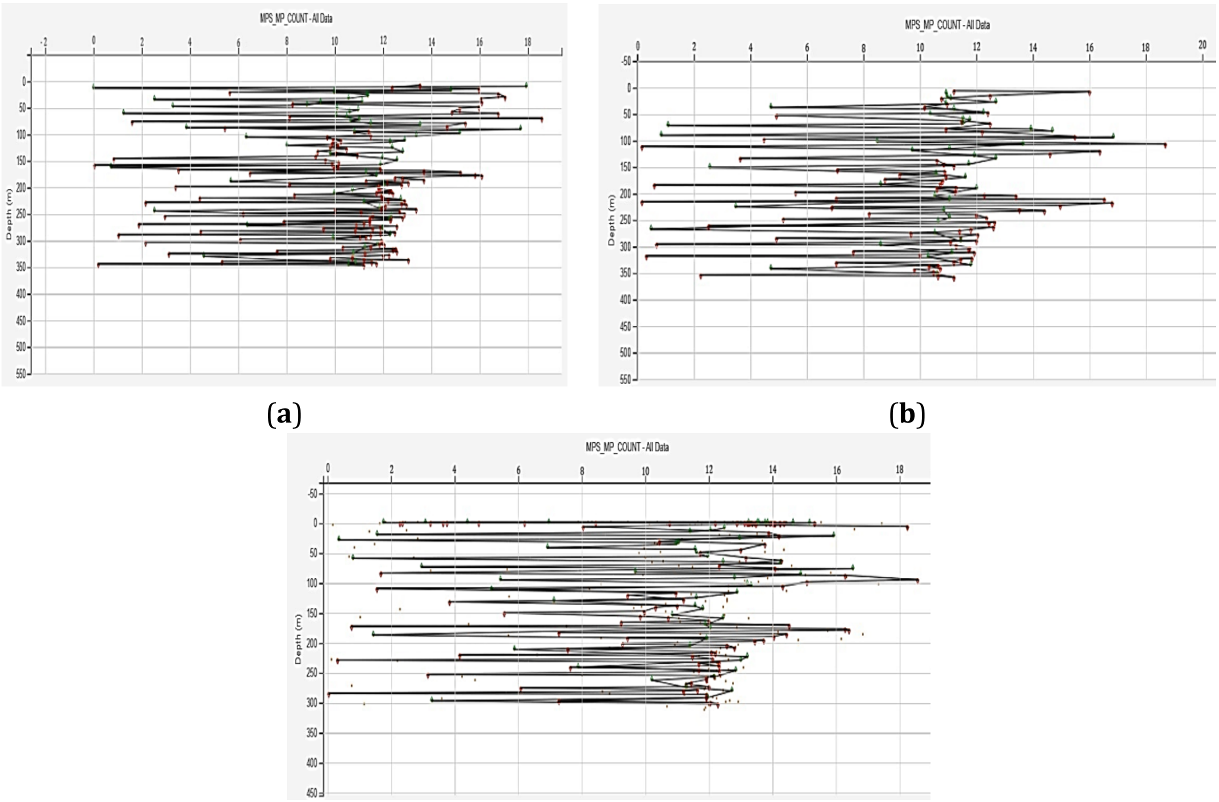
While these measurements provide a quantitative snapshot of pollution levels, it is important to note that the sensor's detection threshold is limited, particularly for particles smaller than 50 μm or composed of low-density polymers. As such, actual microplastic concentrations may be underestimated. In addition, polymeric composition was not analyzed in this study, representing a limitation. However, based on particle appearance and buoyancy, the dominant materials are likely to be polyethylene and polypropylene, which are widely used in packaging and fishing gear and are common in marine debris [30].

To contextualize these findings, a comparison with other studies reveals that the Al Hoceima MPA exhibits moderately high microplastic concentrations. For example, in the Pelagos Sanctuary (France–Italy–Monaco), surface water values ranged between 0.2 and 1.1 items per m^3, while studies in the Gulf of Gabes (Tunisia) and other North African coastal sites have reported values between 2.0 and 5.6 items per m^3 [30]. These comparisons highlight that microplastic pollution within the Al Hoceima MPA is consistent with regional trends but exhibits elevated levels in localized zones, particularly the eastern transects—potentially linked to nearby human activities and currents.

Overall, the analysis of MPS_PAR_COUNT and MPS_MP_COUNT provides a foundation for long-term monitoring and management of microplastic pollution in the Al Hoceima Marine Protected Area. These indicators are crucial for identifying accumulation zones, assessing ecological risks, and informing targeted conservation measures.

In **Figure 2**, the y-axis denotes depth, extending from the surface to approximately 350 meters, while the x-axis reflects microplastic mass (MPS_MP_COUNT). In each graph, red dots signify the glider's descending trajectories, and green dots denote ascending movements, demonstrating the glider's sampling throughout the mission.

The graphs illustrate the microplastic distribution within the water column across various locations or times, presumably associated with glider cycles 415, 443, and 447. All three graphs reveal a distinct pattern: microplastic concentrations are typically elevated near the surface and diminish with increasing depth. This observation aligns with prior findings indicating a minor reduction in microplastic concentrations with increasing depth, especially near the seafloor.



(**a**) (**b**)

(**c**)

Figure 2. Dispersion of microplastic masses (MPS_MP_COUNT) in the western and central regions of the Al Hoceima Marine Protected Area: Glider results from cycles (**a**) 415, (**b**) 443, and (**c**) 447.

The vertical distribution of microplastic mass (MPS_MP_COUNT) across the water column exhibits consistent trends in all three glider profiles. In each case, concentrations peak near the surface—particularly within the upper 20 meters—and gradually decline with increasing depth. Beyond approximately 200 meters, microplastic concentrations reach relatively stable levels, albeit significantly lower than those detected at the surface. This trend reflects the typical behavior of buoyant plastic polymers such as polyethylene and polypropylene, which tend to remain in surface layers unless subject to physical mixing or biofouling.

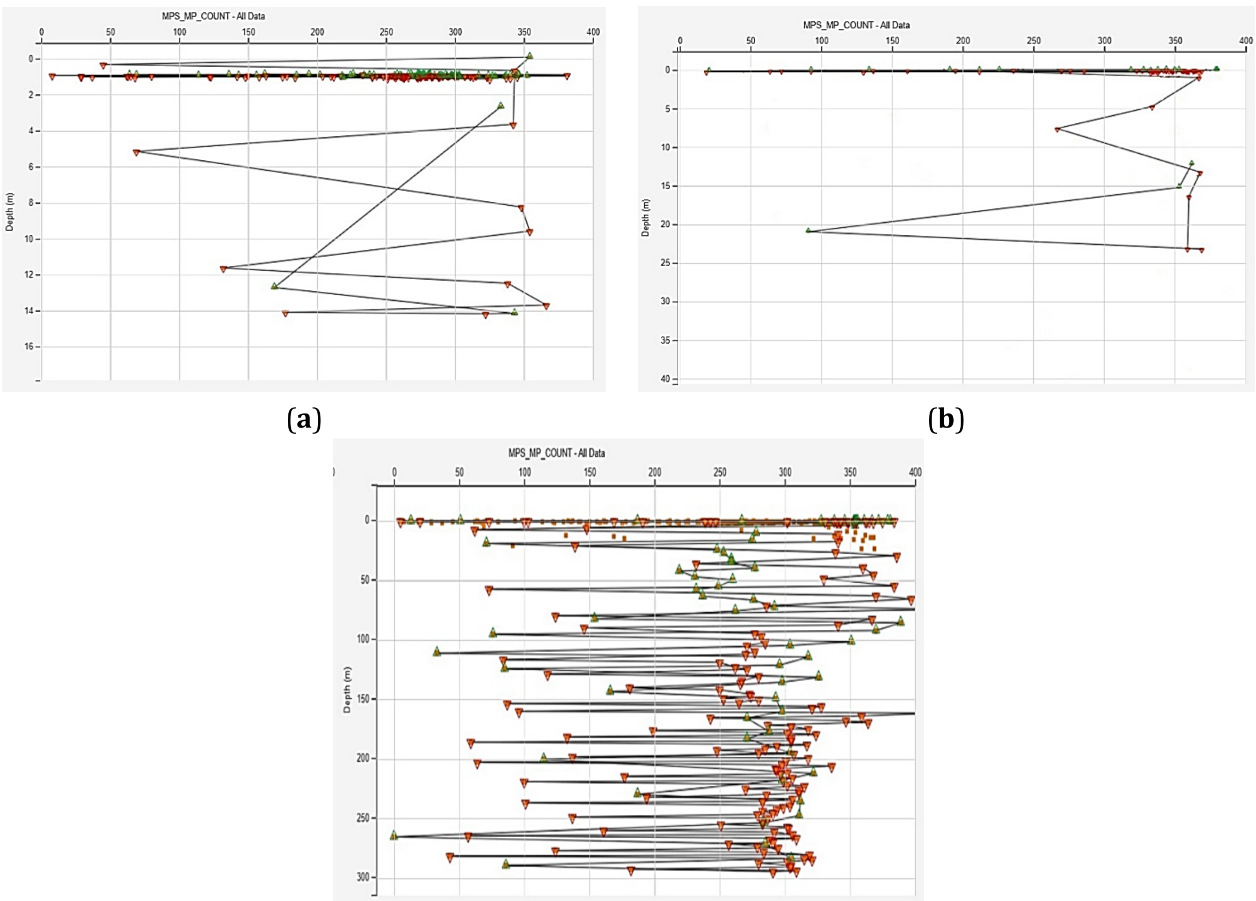
While the general vertical pattern is consistent, notable spatial variability emerges across glider cycles. **Figure 2a**, **2b**, and **2c** (cycles 415, 443, and 447, respectively) reveal differences in both the intensity and vertical extent of microplastic concentrations. **Figure 2a** shows comparatively lower concentrations at mid-water depths (100–200 meters), whereas **Figure 2b**,**c** exhibit elevated peaks, especially in the surface and subsurface layers. These discrepancies may be attributed to localized influences such as nearby human settlements, fishing activity, or harbor discharge, particularly along the eastern and central sectors of the Al Hoceima Marine Protected Area.

The bathymetric context of the region plays an important role in shaping these observed patterns. The Al Hoceima MPA is situated between the continental shelf and the submarine banks of Xaouen and Tofino, where variable seafloor topography interacts with local currents, upwelling systems, and eddies. These hydrodynamic features likely influence the vertical transport, horizontal redistribution, and retention of microplastic particles. The gradual decrease in microplastic mass with depth across all profiles suggests that sinking and deposition may be limited, and that mid-water concentrations are shaped more by current dynamics than by sedimentation.

These findings underscore the importance of incorporating bathymetry, hydrodynamics, and seasonal turbulence into microplastic distribution models. Vertical and horizontal transport processes are critical in determining where microplastics accumulate and how they disperse over time. The elevated concentrations in surface and subsurface layers also highlight the susceptibility of these zones to pollution from surface currents and land-based sources.

Moreover, the absence of polymer-specific identification in this study limits our ability to link particle composition to source origin or potential toxicity. Future investigations should include chemical and morphological characterization of particles using spectroscopic methods to better assess environmental risks and trace pollution pathways.

Understanding these complex spatial and vertical patterns is essential for designing targeted mitigation strategies and prioritizing conservation efforts within MPAs. By integrating physical oceanography with microplastic monitoring, it becomes possible to identify pollution hotspots, assess ecological vulnerability, and inform evidence-based decision-making in marine ecosystem management.



(**a**) (**b**) (**c**)

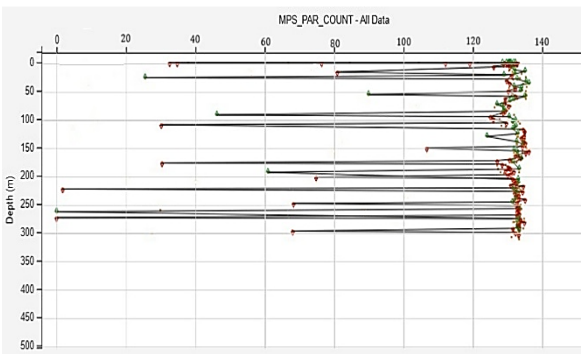
Figure 3. Distribution of microplastic mass (MPS MP COUNT) in the eastern Al Hoceima Marine Protected Area: Glider results from (**a**) cycle 1, (**b**) cycle 2, and (**c**) cycle 3.

Figure 3 presents three vertical profiles labeled (**a**), (**b**), and (**c**), illustrating the distribution of microplastic mass concentration (MPS_MP_COUNT) across different depth intervals within the Al Hoceima Marine Protected Area. The y-axis represents depth, extending from the surface to approximately 40 meters in panels (**a**) and (**b**), and down to ∼250 meters in panel (**c**). The x-axis indicates microplastic mass concentration (mg m^{-3}). Glider movement is denoted by red dots for descent trajectories and green dots for ascent trajectories, capturing the complete sampling cycle during each mission.

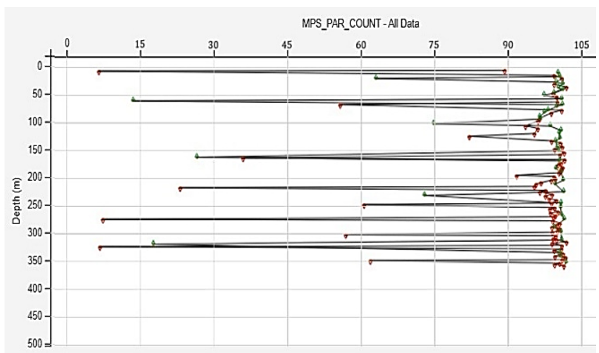
The three profiles correspond to different glider cycles or sampling locations and reveal distinct depth-dependent patterns. In panels (**a**) and (**b**), microplastic concentrations remain relatively stable within the upper 40 meters, suggesting a homogeneous distribution in the surface layer. This may indicate persistent surface accumulation influenced by limited vertical mixing, light polymer buoyancy, and proximity to pollution sources.

In contrast, panel (**c**) offers a deeper profile, extending to 250 meters, and displays a more complex vertical gradient. Concentrations are highest near the surface, gradually declining with depth. Notably, a secondary peak is observed between 50 and 100 meters, followed by a more pronounced reduction in microplastic mass approaching the seafloor. This distribution reflects the typical behavior of microplastics, with surface retention due to buoyancy, and subsurface variability potentially influenced by biofouling, aggregation, or hydrodynamic transport.

The vertical gradient observed in panel (**c**) supports the hypothesis that microplastics accumulate preferentially in surface and subsurface waters, with concentrations diminishing at greater depths due to biological uptake, sedimentation, and decreasing light penetration. These patterns align with previous observations in semi-enclosed seas and highlight the role of local current regimes and topographic features in shaping microplastic dynamics within the MPA.



(**a**)



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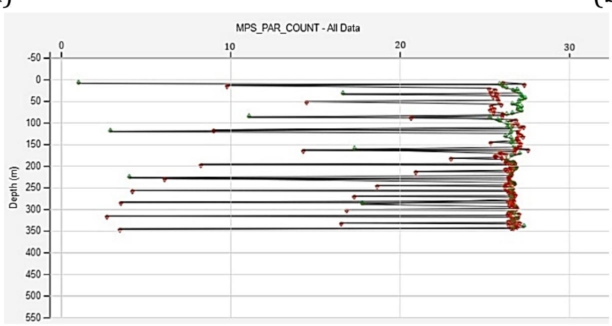

(**c**)

Figure 4. Spatial variation of microplastic particle count (MP PAR COUNT) across depth profiles in the western and central Al Hoceima Marine Protected Area: Glider results from cycles (**a**) 415, (**b**) 443, and (**c**) 447.

This figure presents three vertical profiles labeled (**a**), (**b**), and (**c**), illustrating the spatial distribution of microplastic particle count (MPS_PAR_COUNT) across different depth profiles within the Western and Central sectors of the Al Hoceima Marine Protected Area (MPA). The y-axis represents depth, extending from the surface down to approximately 350 meters, while the x-axis indicates microplastic particle concentration (in particles per liter, par L^{-1}). Red dots represent the descent path of the glider, and green dots correspond to the ascent, capturing the complete sampling journey across each glider cycle.

Graph (**c**) corresponds to cycle 415, conducted in the westernmost part of the MPA. Particle concentrations remain relatively low, averaging around 26 par L^{-1}, with minor variability throughout the water column. This profile suggests limited microplastic contamination in this zone, likely due to lower exposure to direct anthropogenic inputs and possibly greater water exchange or flushing from open sea currents.

Moving eastward, Graph (**b**) depicts cycle 443, located in the central region of the MPA. Here, microplastic concentrations increase to approximately 100 par L^{-1}. The vertical distribution remains relatively uniform, suggesting that mixing processes and vertical turbulence may be redistributing microplastic particles throughout the column. The central location may be influenced by coastal activities, maritime traffic, or fishing operations, contributing to elevated and evenly distributed microplastic levels.

Graph (**a**), representing cycle 447 in the easternmost area of the MPA, shows the highest concentrations, reaching up to 135 par L^{-1}. This indicates a significant increase in microplastic contamination compared to the western and central zones. The profile displays a pronounced gradient, with concentrations peaking near the surface and decreasing with depth. These results suggest intensified pollution pressure in the eastern zone, potentially driven by urban runoff, population density, port activity, and limited flushing due to coastal topography.

Across all three graphs, a consistent trend is observed: microplastic concentrations are highest in surface waters and decline with depth. This vertical gradient aligns with typical microplastic behavior in marine systems, where buoyant polymers accumulate in upper layers due to low density, surface currents, and limited vertical transport. In Graph (**a**), the surface accumulation is particularly pronounced, supporting the hypothesis that land-based sources and nearshore activities are contributing to elevated surface-level contamination.

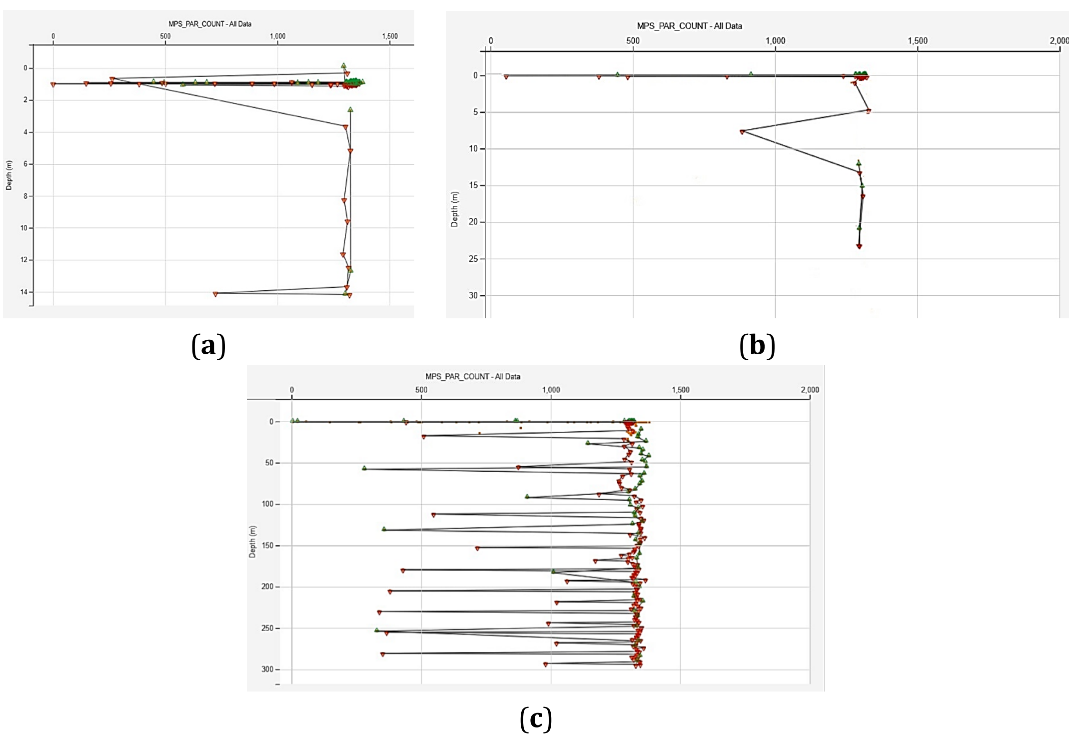

Figure 5. Depth-resolved distribution of microplastic particle concentration (MP PAR COUNT) in the eastern region of Al Hoceima Marine Protected area: Glider outcomes from cycles (**a**) 1, (**b**) 2, and (**c**) 3.

In contrast, Graphs (**b**) and (**c**) show a more homogeneous vertical distribution, indicating that local hydrodynamics, such as vertical mixing and turbulent diffusion, may be facilitating deeper particle dispersion, despite lower overall concentrations. This comparison across glider cycles emphasizes the spatial heterogeneity of microplastic pollution within the MPA and highlights the importance of both regional oceanography and human activity in shaping microplastic distribution patterns.

Graphs (**a**), (**b**), and (**c**) present depth-resolved profiles of microplastic particle count (MPS_PAR_COUNT) obtained from glider missions during cycles 1, 2, and 3 in the eastern sector of the Al Hoceima Marine Protected Area (MPA). The y-axis represents depth (0–350 meters), while the x-axis indicates microplastic particle concentration in particles per liter (par L^{-1}). As in previous figures, red dots represent glider descents, and green dots represent ascents, reflecting continuous data acquisition during each cycle.

All three profiles demonstrate consistently high microplastic concentrations, exceeding 1300 par L^{-1} in the surface and subsurface layers, confirming earlier observations of elevated contamination in the upper water column. These elevated values suggest either persistent surface-level sources, such as urban runoff or maritime activity, or limited vertical dispersion due to stratified water masses and low turbulence.

Across all graphs, a general trend of decreasing concentration with depth is evident, although the decline is not uniform. Notably, Graph (**c**) (cycle 3) displays a broader vertical spread, with detectable concentrations extending into mid-depth ranges (100–200 meters). This pattern implies that microplastic particles may be retained or redistributed at intermediate depths, possibly through biofouling, sinking-aggregation processes, or subsurface currents.

Graph (**a**) (cycle 1) shows consistently high concentrations (>1300 par L^{-1}) throughout most of the profile, with only a slight decline beyond 150 meters, indicating strong surface accumulation with limited downward transport. Graph (**b**) (cycle 2) follows a similar trend, though with a slightly sharper decline beyond 100 meters, suggesting vertical stratification or mixing barriers in this zone. In contrast, Graph (**c**) (cycle 3) exhibits both higher peak concentrations and greater vertical penetration, highlighting potential spatial variability influenced by dynamic hydrodynamic conditions or proximity to point-source pollution.

These profiles emphasize the complexity of microplastic distribution within the water column, where accumulation is shaped by a combination of physical oceanographic processes, particle properties, and human pressures. The particularly high surface concentrations observed in all three cycles further underscore the need for localized pollution mitigation, especially in high-impact zones within the eastern MPA.

4.2. Currents Analysis

To enhance our research, we assessed contemporary data from the Puertos del Estado platform [31]. The platform features visualization tools, including maps, graphs, and charts, to convey data clearly. Users can customize their displays to concentrate on specific locations, parameters, or time frames, thereby enabling thorough analysis and informed decision-making.

Consequently, we selected three coordinates (2033063, 2034063, and 2035063) adjacent to our research locations within the marine protected zone (**Figure 6**) The numerical data (**Tables 1–3**) offered insights into the intensity and trajectory of current propagation during the study period, enhancing our comprehension of the spatial distribution of microplastic pollution.

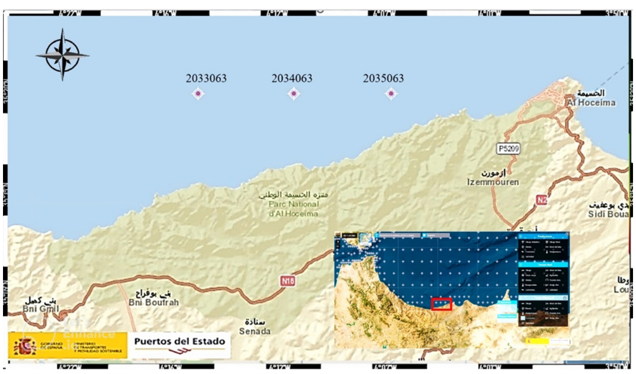

Figure 6. Map for spatial analysis of current data adjacent to study points (2033063, 2034063, and 2035063) in the Al Hoceima Marine Protected Area utilizing the Puertos del Estado platform [31].

Table 1. Comprehensive analysis of average current velocities (cm s^{-1}) by orientation and velocity range for November 2020 at SIMAR point 2033063.

Direction	Degrees	<= 0.2	2.0	4.0	6.0	8.0	10.0	12.0	> 20.0	Total
N	0			0.139	0.694	0.694	0.417			2.917
NNE	22.5			0.278	0.278	0.139				2.5
NE	45		0.278	1.111	0.694	0.694	0.278	0.972	0.556	5
ENE	67.5		1.25	0.556	2.222	1.111	0.417	2.222		13.472
E	90		2.222	1.389	1.111	0.833	0.417	1.389		14.167
ESE	112.5		0.278	0.278		0.833	0.278			3.889
SE	135		0.139							2.917
SSE	157.5		0.139	0.278	0.278	0.139				1.528
S	180	0.139	0.139	0.139	0.556					1.389
SSW	202.5			0.139	0.139	0.139				1.25
SW	225		0.278	0.278	0.139					1.25
WSW	247.5	0.556	0.556	0.694	0.833	0.556	0.972			6.667
W	270		0.278	1.111	1.528	1.528	0.972			24.722
WNW	292.5		0.278		0.694	0.972	0.694			11.111
NW	315	0.139	0.278	0.972	0.694	0.278		0.278		6.528
NNW	337.5	0.139	0.278	0.694	0.417	0.694	0.417			3.889
Total		2.222	0.556	6.111	10.833	8.333	8.889	4.583		100

The SIMAR Point 2033063 (**Table 1**) presents a comprehensive overview of the average current speed in centimeters per second for different directions in November 2020. The data is categorized based on the angle (measured in degrees) and the range of current speeds, ranging from less than 0.2 cm s^{-1} to over 20.0 cm/s. No currents are detected in the North direction within the ranges of ≤ 0.2 cm s^{-1} and 2.0 cm s^{-1}. The average velocity for the 4.0 cm s^{-1} range is 0.139 cm s^{-1}, while for the 6.0 cm s^{-1} range it is 0.694 cm s^{-1}. These values yield a total average velocity of 1.944 cm s^{-1}. The current flows in the East-Northeast direction at an angle of 67.5°. The average speed of the current is 0.139 cm s^{-1} for the 4.0 cm s^{-1} range, 0.556 cm s^{-1} for the 6.0 cm s^{-1} range, and 0.694 cm s^{-1} for the 8.0 cm s^{-1} range. The overall percentage of the current is 13.472%.

West (270.0°): The average velocity is 0.278 cm s^{-1} for the 2.0 cm s^{-1} interval, 1.111 cm s^{-1} for the 4.0 cm s^{-1} interval, and 1.111 cm s^{-1} for the 6.0 cm s^{-1} interval, resulting in a total of 24.722%.

The **Table 2** presents data on the average current velocity in cm s^{-1} for different directions in November 2020, specifically for SIMAR Point 2034063. The data is classified according to direction and current velocity ranges.

- North (0.0°): The average velocity of the current is 0.139 cm s^{-1} for the range of 4.0 cm s^{-1} and 0.556 cm s^{-1} for the range of 6.0 cm s^{-1}, resulting in a total average velocity of 2.361 cm s^{-1}. The average current speed in the East-Northeast direction is 0.139 cm s^{-1} for the range of 4.0 cm s^{-1}, 0.556 cm s^{-1} for the range of 6.0 cm s^{-1}, and 0.972 cm s^{-1} for the range of 8.0 cm s^{-1}, resulting in a total percentage of 7.778%.
- West (270.0°): The mean velocity is 0.278 cm s^{-1} for the 2.0 cm s^{-1} interval, 0.833 cm s^{-1} for the 4.0 cm s^{-1} interval, and 1.111 cm s^{-1} for the 6.0 cm s^{-1} interval, yielding a total percentage of 25.556%.

The dataset for SIMAR Point 2035063 presents the average current velocity in centimeters per second across various directions. The data is classified according to direction and velocity ranges for November 2020.

- North (0.0°): The mean velocity of the current is 0.139 cm s^{-1} within a range of 4.0 cm s^{-1}, yielding a total of 1.944%. The current is directed East-Northeast at an angle of 67.5°. The average speed of the current is 0.694 cm s^{-1} over a range of 8.0 cm s^{-1}, 0.972 cm s^{-1} over a range of 10.0 cm s^{-1}, and 1.111 cm s^{-1} over a range of 12.0 cm s^{-1}, yielding a cumulative speed of 11.250%.
- West (270.0°): The average velocity for the 2.0 cm s^{-1} range is 0.278 cm s^{-1}, for the 4.0 cm s^{-1} range is 0.833 cm s^{-1}, and for the 8.0 cm s^{-1} range is

Table 2. Comprehensive analysis of average current velocities (cm s^{-1}) by orientation and velocity range for November 2020 at SIMAR point 2034063.

Direction	<= 0.2	2.0	4.0	6.0	8.0	10.0	12.0	14.0	> 20	Total
N		0.139	0.556	0.417	0.417	0.694	0.139	0.139		2.361
NNE		0.278	0.556	0.694	0.278	0.278	0.278	0.278		2.361
NE	0.694	0.833	0.417	0.556	0.972	1.111	0.278	0.278	0.278	4.861
ENE	0.139	0.556	0.972	0.694	0.694	1.111	0.139	0.417	0.278	7.778
E		0.556	0.694	0.833	0.972	1.389	0.417	0.278	0.417	5.972
ESE	0.417	0.694	0.833	0.972	1.389	1.111	0.556	0.139	0.139	5.139
SE		0.278	0.417	0.833	0.278	0.278	0.278	0.278	0.278	2.778
SSE	0.417	0.278	0.278	0.417	0.139	0.278	0.139	0.278	0.278	2.778
S	0.278	0.417	0.556	0.417	0.139	0.278	0.139	0.139		2.361
SSW		0.278	0.278	0.278	0.139	0.139	0.139			1.25
SW	0.417	0.556	0.556	0.278	0.139	0.278	0.278	0.278	0.139	2.083
WSW	0.278	0.278	0.556	0.417	0.833	0.278	0.556	0.278		2.639
W	0.139	0.417	0.833	0.833	0.972	0.972	0.833	0.139		6.083
WNW	0.417	0.694	1.111	1.25	1.667	1.25	0.417	0.278	0.278	7.778
NW	0.556	0.833	0.972	1.389	1.25	1	0.694	0.139	0.139	7.417
NNW	0.139	0.278	0.694	0.833	0.972	1.111	0.972	0.139	0.139	5.833
Total	3.75	7.639	9.306	12.361	11.944	11.667	6.139	3.75	2.361	68.167

1.667 cm s^{-1}, resulting in a cumulative percentage of 27.361%.

The variations in hydrodynamic conditions significantly influence the spatial distribution of microplastic particles and other pollutants in the marine environment. The data for SIMAR Point 2033063, collected from November 10, 2020, to December 12, 2020, demonstrate variations in current speed, with peak velocities observed in mid-November and early December, indicating intervals of heightened water flow. The data for SIMAR Point 2033063, collected from November 10, 2020, to December 12, 2020, demonstrates variations in current speed, with peak velocities observed in mid-November and early December, indicating intervals of heightened water flow. This trend is marked by multiple sudden fluctuations in current velocity, pointing to potential influences such as meteorological conditions, tidal patterns, or other oceanographic phenomena.

The analysis of SIMAR Point 2034063 reveals a comparable pattern to that of SIMAR Point 2033063. The discernible upward trend leading up to early December and the presence of spikes indicate a uniformity in oceanic conditions between the two points. This consistency suggests that the hydrodynamic factors driving the currents are impacting these regions in a similar way.

The graph for SIMAR Point 2035063, although not explicitly depicted, exhibits a trend analogous to that of SIMAR Points 2033063 and 2034063. The data indicate speed fluctuations between 0 cm s^{-1} and 0.6 cm s^{-1} throughout the study period. The emergence of peaks in mid-November and early December, coupled with a steady rise in current velocity as early December approaches, substantiates the hypothesis that external factors, such as tidal forces or meteorological phenomena, are affecting current dynamics at various locations. The uniformity noted across all three points bolsters the reliability of the data and underscores the impact of regional hydrodynamic patterns on the dispersion of pollutants, including microplastics, within the MPA.

Directional Analysis

Each diagram (**Figure 7**) illustrates the prevailing current directions and their respective velocities for each SIMAR Point. The observed patterns reveal that the dominant currents at all three locations predominantly flow in the east and west directions, displaying elevated average speeds. Velocity variations are contingent upon direction, with peak speeds generally recorded in the East-Northeast and West orientations. In summary, the average current speeds demonstrate considerable movement in the East and West directions, indicating robust lateral currents in November 2020.

Table 3. Comprehensive analysis of average current velocities (cm s^{-1}) by orientation and velocity range for November 2020 at SIMAR point 2035063.

Direction	<= 0.2	2.0	4.0	6.0	8.0	10.0	12.0	14.0	> 20	Total
N		0.139	0.556	0.417	0.417	0.694	0.139	0.139		2.361
NNE		0.278	0.556	0.694	0.278	0.278	0.278	0.278		2.361
NE	0.694	0.833	0.417	0.556	0.972	1.111	0.278	0.278	0.278	4.861
ENE	0.139	0.556	0.972	0.694	0.694	1.111	0.139	0.417	0.278	7.778
E		0.556	0.694	0.833	0.972	1.389	0.417	0.278	0.417	5.972
ESE	0.417	0.694	0.833	0.972	1.389	1.111	0.556	0.139	0.139	5.139
SE		0.278	0.417	0.833	0.278	0.278	0.278	0.278	0.278	2.778
SSE	0.417	0.278	0.278	0.417	0.139	0.278	0.139	0.278	0.278	2.778
S	0.278	0.417	0.556	0.417	0.139	0.278	0.139	0.139		2.361
SSW		0.278	0.278	0.278	0.139	0.139	0.139			1.25
SW	0.417	0.556	0.556	0.278	0.139	0.278	0.278	0.278	0.139	2.083
WSW	0.278	0.278	0.556	0.417	0.833	0.278	0.556	0.278		2.639
W	0.139	0.417	0.833	0.833	0.972	0.972	0.833	0.139		6.083
WNW	0.417	0.694	1.111	1.25	1.667	1.25	0.417	0.278	0.278	7.778
NW	0.556	0.833	0.972	1.389	1.25	1	0.694	0.139	0.139	7.417
NNW	0.139	0.278	0.694	0.833	0.972	1.111	0.972	0.139	0.139	5.833
Total	3.75	7.639	9.306	12.361	11.944	11.667	6.139	3.75	2.361	68.167

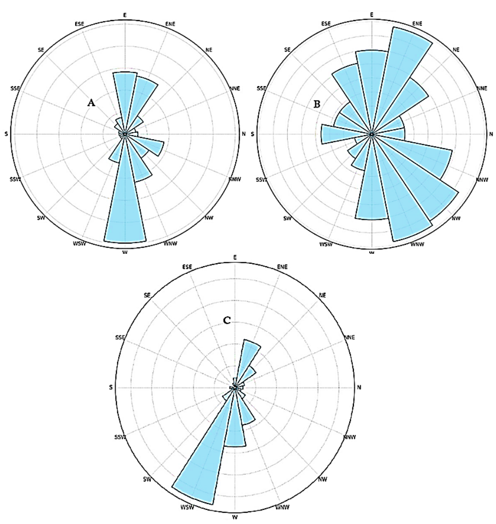

Figure 7. Rose diagrams illustrate the distribution of current directions and velocities, offering a detailed perspective on the dominant currents at the three locations: (**A**) SIMAR 2033063, (**B**) 2034063, and (**C**) 2035063.

A comprehensive understanding of the transportation mechanisms influencing pollution hotspots in the Al Hoceima Marine Protected Area (MPA) can be attained by synthesizing current data with information on microplastic concentrations. The discovery of these patterns is vital for formulating targeted strategies to mitigate their consequences and optimize the effectiveness of marine conservation efforts. Currents exert a significant impact on the movement and dispersion of water masses and suspended particles, including microplastics. Through the analysis of contemporary patterns, researchers can track the spread of pollutants in the marine ecosystem, which is crucial for pinpointing probable sources of microplastics and predicting their dispersal within the Marine Protected Area [32].

Through the examination of contemporary data concerning microplastic concentrations, researchers can identify particular regions within the MPA where microplastics are prone to accumulate. When currents converge or create vortices, they can entrap floating debris [33], resulting in localized areas of microplastic pollution. Identifying these high-activity regions is crucial for prioritizing conservation initiatives and executing targeted strategies to alleviate the effects of microplastic pollution.

Furthermore, ocean currents are essential in shaping the biological realm by affecting nutrient transport, habitat connectivity, and larval distribution. These factors collectively influence marine biodiversity and ecosystem functionality. Currents can convey microplastics, resulting in interactions with marine organisms and ecosystems. These interactions may yield substantial biological repercussions, including marine species consuming microplastics or sustaining physical harm to coral reefs and seagrass meadows. Comprehending the movement of currents in relation to microplastics aids in evaluating potential ecological hazards and guides conservation initiatives [33, 34].

Ongoing surveillance of prevailing conditions yields real-time data, enhancing the efficacy of MPA management. By synthesizing contemporary data with additional environmental variables, managers can examine the spatial and temporal dynamics of microplastic pollution [35], enabling them to track changes over time. This monitoring approach allows for the implementation of necessary modifications to conservation strategies, ensuring a more effective response to emerging environmental challenges [36].

4.3. Hydrological Characteristics of the Investigated Region

Additionally, we employed the ArcGIS platform [37] to acquire hydrological maps of Morocco (**Figure 8**), emphasizing significant freshwater streams that traverse Al Hoceima National Park and extend into its marine area. Three principal streams have been identified, each originating from rural areas characterized by minimal urbanization.

- Oued Tarmest, also known as Bousakour, is a stream that directly empties into the coastal area, ending at the Bousakour shoreline. Originating in the rural hinterlands, Oued Tarmest contributes a significant amount of freshwater to the coastal environment pertaining to the Al Hoceima Marine Reserved Area. The Mediterranean hydrological regime exhibits seasonal flow variability [38]. High flow transpires during the rainy season from November to March, while low flow occurs during the dry season from April to October. Sediment transport is a significant characteristic, as the rainy season leads to increased sediment loads due to soil erosion in the rural catchment area. Although the water quality is typically acceptable, slight urban development may affect it, and there exists a risk of pollutants entering through agricultural runoff [38].
- Oued Snada is a notable waterway that flows into Bades, contributing freshwater directly to the marine ecosystem. The origin of the issue resides in rural regions that have undergone minimal urban development, influencing the water quality dynamics in the safeguarded coastal zone. Similar to Oued Tarmest, Oued Snada adheres to the Mediterranean hydrological regime, demonstrating pronounced seasonal fluctuations in its flow patterns. Erosion and sedimentation are pivotal in sediment transport, especially during the rainy season, which profoundly influences coastal sediment dynamics [38]. The freshwater influx from Oued Snada is essential for sustaining the hydrological linkage between terrestrial and marine ecosystems. It is crucial for nutrient transfer and the preservation of ecological equilibrium.
- The Oued Beni Boufrah originates in Cala Iris and passes through agricultural regions before arriving at the marine ecosystem. The freshwater influx from this stream is crucial for sustaining biological balance and nutrient flow in the Al Hoceima Marine Protected Area. Its principal characteristics encompass flow variability, exhibiting elevated flow in winter and diminished flow in summer, consistent with the typical Mediterranean climate. The agricultural influence on this watercourse heightens the probability of agricultural runoff, which may compromise water quality through the introduction of surplus nutrients and pesticide residues. Moreover, Oued Beni Boufrah contributes to the ecosystem by supplying vital freshwater resources that sustain marine biodiversity and affect the resilience of coastal ecosystems in recovering from disturbances [38].

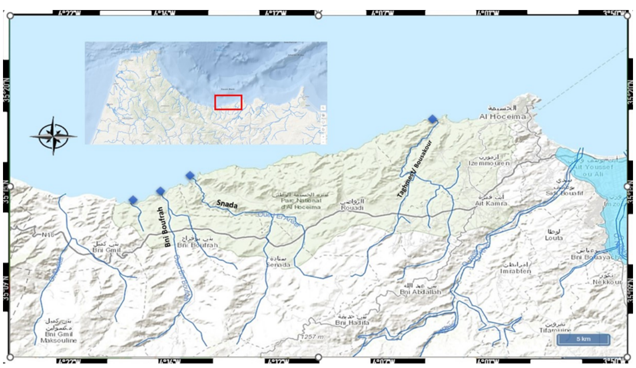

Figure 8. Hydrology map of the studied area: Key freshwater streams and river mouths in Al Hoceima National Park and its maritime extension [37].

Understanding the hydrological dynamics of these streams is essential for evaluating the effects of freshwater imports on marine biodiversity, pollution transport pathways, and ecosystem resilience in the Al Hoceima

Marine Protected Area. These streams serve as conduits for freshwater runoff from adjacent rural regions, regulating the exchange of water and nutrients between terrestrial and marine ecosystems. Grasping these dynamics is vital for assessing the influence of freshwater inputs on marine biodiversity, pollutant dispersion, and the resilience of the marine ecosystem within the protected area.

5. Discussion

The study underscores the occurrence of microplastics in Marine Protected Areas (MPAs), yet it may exaggerate the significance of these results. The identification of microplastics in MPAs does not necessarily imply their ineffectiveness; instead, it may suggest that pollution is a pervasive concern affecting all marine ecosystems, irrespective of their protection status. Emphasizing MPAs might distract from more extensive pollution sources that influence both protected and unprotected regions. Additionally, the potential impact of atmospheric deposition of microplastics was not addressed, which could represent a considerable source of contamination in these areas.

Microplastics are commonly detected in unspoiled marine ecosystems at concentrations below 1 μg L^{-1} [2–39]. These environments exhibit minimal human impact and low pollution levels, leading to a sparse distribution of microplastic particles. Conversely, microplastic concentrations in highly contaminated areas, such as those adjacent to urban runoff, may exceed 100 μg L^{-1} [39]. The increased levels signify a significant human influence on marine ecosystems, where plastic debris accumulates as a result of urbanization, industrial operations, and inadequate waste management practices [40].

The observed higher microplastic content in the first three cycles of the eastern part of the marine protected area (**Figures 3** and **5**), notably in the extreme eastern section near Inouaren fishing harbor and the city of Al Hoceima, is an intriguing element of our study. This concentration is commonly reported as the number of microplastic particles per unit volume of water, typically expressed as particles per liter (particles L^{-1}) or mass of microplastic per cubic meter (mg m^{-3}) [41]. Conversely, microplastic concentrations were minimal in Cycles 415, 443, and 447 within the western section of the marine protected area. This disparity highlights that microplastic pollution in the Al Hoceima MPA is confined to particular regions.

To improve our comprehension of the spatial distribution of microplastics within the Marine Protected Area (MPA), we integrated data from recent measurements and hydrological maps. The hydrological maps of the region identified three significant streams—Oued Tarmest, Oued Snada, and Oued Beni Boufrah—that discharge freshwater directly into the oceanic environment within the MPA [38]. These streams, originating from rural areas, act as conduits for pollutants, including microplastics, to infiltrate coastal waters. The relationship between terrestrial activities and marine ecosystems highlights the significant impact of land-based actions on oceanic health. It underscores the essential requirement for integrated watershed management to mitigate the influx of pollutants into marine ecosystems.

Moreover, data from the Puertos del Estado platform indicated that the dominant current velocities within the MPA were approximately 0.5 cm s–1, as presented in **Table 1**. These currents substantially affect the dispersion and deposition of microplastics along coastlines, influencing their distribution patterns in the marine ecosystem [40–42]. Comprehending hydrodynamic dynamics is essential for assessing the transport of microplastics in marine ecosystems and pinpointing regions with elevated concentrations [2].

Al Hoceima MPA, characterized by its agricultural surroundings and limited water flow, faces considerable effects from microplastics in its coastal zones. Decreased stream flow leads to a reduction in particle transport, especially microplastics, from inland sources to coastal areas. Microplastics tend to accumulate and endure in coastal regions instead of being rapidly conveyed to the open ocean.

In this context, microplastic pollution is predominantly attributed to local sources, including coastal towns, maritime activities, and tourism, rather than contributions from inland rivers. These particular inputs may lead to increased concentrations of microplastics in coastal waters. Furthermore, diminished energy levels due to low stream flow may promote sediment deposition and microplastic accumulation in benthic ecosystems and coastal regions. This accumulation may yield ecological repercussions, potentially detrimental to marine organisms via ingestion or tissue accumulation, thereby disturbing the natural equilibrium of the marine ecosystem in the safeguarded area. To formulate effective conservation strategies that mitigate pollution and preserve the natural equilibrium of marine protected areas, it is crucial to precisely identify and comprehend the sources and pathways of microplastics [43].

- Investigation Requirement: Microplastics in Sedimentary Deposits of Marine Protected Areas

Despite considerable attention on the presence of these substances in surface waters and marine organisms, their accumulation in sediments, especially within Marine Protected Areas, remains a subject requiring further exploration [32]. Plastics with a density greater than seawater, such as polyethylene and polypropylene, typically submerge and accumulate on the ocean floor upon entering marine ecosystems [44]. This behavior is determined by the particles' material composition and morphology. In contrast, low-density microplastic particles, such as polystyrene and polyethylene terephthalate (PET), typically exhibit buoyancy, allowing them to either float on the ocean surface or remain suspended in the water column. These particles can traverse considerable distances before ultimately settling [45].

Contaminants and the aggregation of marine organisms on submerged surfaces significantly influence the behavior of microplastics in marine ecosystems [46]. Biofouling occurs when organisms increase the density of microplastic surfaces via colonization, potentially resulting in the sinking of previously buoyant microplastics and contributing to sediment accumulation [7].

The accumulation of microplastics in marine sediments raises multiple environmental issues. Initially, sediments act as long-term storage areas for microplastics, which do not degrade as quickly as they do in surface waters, leading to the extended presence of these pollutants [47]. Their capacity to endure for prolonged durations intensifies their potential impact on marine ecosystems. Moreover, microplastics embedded in sediments may interact with benthic organisms, potentially infiltrating food chains and resulting in adverse ecological effects [48]. These interactions can impair ecosystem functionality and threaten biodiversity, particularly in vulnerable marine environments. Furthermore, sediment dynamics affected by currents and seasonal fluctuations can resuspend buried microplastics into the water column [49]. Remobilization may persist in exposing the environment and exacerbating pollution in marine ecosystems [32].

Comprehending the mechanisms of biofouling, sediment deposition, and the potential ecological ramifications of microplastics in marine sediments is essential for formulating effective strategies and policies to alleviate their environmental impact and safeguard marine biodiversity [35–50]. To improve the understanding and management of microplastic pollution in Marine Protected Areas, several essential recommendations are suggested. Initially, it is imperative to perform comprehensive spatial and temporal analyses throughout all seasons and locations within Marine Protected Areas (MPAs). This research will elucidate the extent of microplastic deposition and accumulation rates, furnishing essential data for the formulation of effective conservation strategies. Furthermore, it is essential to implement standardized protocols for the collection of sediment samples and the execution of microplastic analyses. This standardization guarantees the reliability and uniformity of data, enabling thorough evaluations of the prevalence and trends of microplastics over time [51]. It is essential to assess the effectiveness of current MPA regulations and management strategies in mitigating microplastic pollution and its accumulation. Such assessments are vital for refining management approaches and bolstering the ecological resilience of MPAs, thus safeguarding marine biodiversity and ecosystem health [52].

The results underscore the urgent necessity for robust marine conservation policies to tackle the pervasive problem of microplastic pollution. Microplastics, chiefly derived from urban runoff, fishing practices, and coastal development, present significant risks to marine biodiversity [53]. The identification of pollution hotspots in the Al Hoceima Marine Protected Area highlights the necessity of enforcing stringent regulations and adopting sustainable practices to mitigate the influx of plastic waste into marine ecosystems [54].

An analysis of microplastic concentrations within various regions of the Al Hoceima Marine Protected Area indicates notable disparities. Concentrations of microplastics are markedly elevated in the eastern sectors adjacent to human settlements, whereas diminished levels are observed in the western regions characterized by reduced urbanization [55]. This regional variation underscores the efficacy of Marine Protected Areas (MPAs) in alleviating pollution effects by reducing human interference and safeguarding susceptible marine ecosystems from plastic contamination.

Marine Protected Areas (MPAs) are crucial for mitigating marine pollution by offering refuge for marine organisms and ecosystems. Marine Protected Areas (MPAs) are essential in mitigating plastic waste accumulation and safeguarding marine biodiversity through the regulation of human activities and the promotion of sustainable practices [56]. The research conducted in Al Hoceima illustrates that spatial management strategies employed in Marine Protected Areas (MPAs) augment ecosystems' resilience and recovery from disturbances, while also fostering habitat connectivity, essential for the survival and well-being of marine species [57]. The findings underscore the vital significance of Marine Protected Areas (MPAs) in global conservation efforts, highlighting their capacity to facilitate sustainable marine management and safeguard susceptible marine ecosystems from microplastic pollution [58].

This study offers comprehensive measurements of microplastic concentrations across the water column, from the surface to the seafloor [50]. This also provides insight into the bathymetry of the area where the operation was conducted, noting that the marine protected area is situated in a corridor between the continental shelf and the banks of Xaouan and Tofino. This geographic positioning influences the hydrodynamic conditions and, consequently, the accumulation and movement of microplastics. Currents within this corridor can enable the transportation of microplastics, contributing to their accumulation in certain areas while potentially dispersing them in others. Understanding these dynamics is crucial for effective conservation planning and for targeting mitigation measures to minimize the environmental impact of microplastic contamination in this sensitive region [59, 60].

6. Conclusions

This study conducted within the Al Hoceima Marine Protected Area (MPA) offers valuable insights into the prevalence, vertical distribution, and spatial variability of microplastic pollution in a region of ecological significance. Through the integration of autonomous underwater glider data, hydrological mapping, and spatial analysis, we have identified pollution hotspots and revealed the complex dynamics of microplastic accumulation across different depth profiles and geographic zones.

Our results indicate that microplastic concentrations are particularly elevated in the eastern portion of the MPA, especially near urbanized coastal areas and fishing ports such as Inouaren. These findings highlight the direct influence of land-based activities, including urban runoff, maritime traffic, and fishing operations, on microplastic pollution levels. The distribution patterns observed also reflect the role of hydrodynamic forces and coastal currents, which facilitate the horizontal and vertical transport of microplastics and contribute to their persistence in surface and subsurface waters.

Although several freshwater inputs—such as Oued Tarmest, Oued Snada, and Oued Beni Boufrah—discharge into the MPA, our analysis suggests that these streams are not the primary sources of microplastic contamination. Instead, the evidence points to regional anthropogenic pressures, including tourism, port operations, and insufficient coastal waste management systems, as key contributors to pollution in the area.

Importantly, the study reinforces the role of MPAs in mitigating environmental degradation. Zones with limited human presence demonstrated lower microplastic concentrations, illustrating the potential of MPAs to preserve marine biodiversity and enhance ecosystem resilience when effectively managed. However, achieving these outcomes requires the implementation of stricter waste control policies, enhanced monitoring systems, and active community engagement in sustainable practices.

Future research is essential to build on these findings. Long-term monitoring programs, combined with advanced modeling techniques, will be critical for projecting trends, identifying sources, and guiding adaptive management. Moreover, detailed investigations into microplastic chemical composition, toxicity, and ecological interactions—especially concerning local marine organisms—are urgently needed to inform evidence-based conservation policies.

Addressing microplastic pollution is a multidimensional challenge that calls for interdisciplinary, cross-sector, and international collaboration. By applying the insights gained from this research and promoting innovative approaches to pollution reduction, we can contribute to the protection of marine ecosystems and ensure the sustainable stewardship of our oceans for future generations.

Author Contributions

Conceptualization: H.B.; Methodology: H.B.; Software: A.E.M.; Validation: H.B., A.D., A.E.M.; Formal Analysis: H.B.; Investigation: H.B.; Resources: H.B.; Data Curation: H.B.; Writing—Original Draft Preparation: A.E.M., A.D., M.M.; Writing—Review and Editing: H.B., A.D., A.E.M., S.K., M.M.; Visualization: H.B. All authors have reviewed and approved the final version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study are not publicly available as they are the property of the ODYSSEA project. Access may be granted upon reasonable request and with permission from the project administration: https://odysseaplatform.eu/.

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Conflicts of Interest

The authors declare no conflicts of interest. They affirm that no personal or financial circumstances influenced the objectivity of the reported research. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results

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