MAPPING LITTER TRAJECTORY USING "GNOME" MODEL ALONG EGYPTIAN MEDITERRANEAN COAST

Noha S. Sayed[1]; Aly N. El Bahrawy[2]; Hanan A. Farag[3] and Noha S. Donia[4]

1) Natural Conservation Sector, Egyptian Environmental Affairs Agency 2)Faculty of Engineering, Ain Shams University 3) National Water Research Center 4) Faculty of Graduate Studies and Environmental Research, Ain Shams University

ABSTRACT

Marine litter (ML) has recently become one of the most global prevalent pollution problems adversely affecting oceans and waterways. This study aimed to explore the vulnerability of Alexandria Governorate coastal locations to ML using General National Oceanic and Atmospheric Administration Operational Oil Modeling Environment (GNOME) software. Hypothetical release of ML from El-Shatby beach was simulated through three windage classes during wet and dry periods. Quantitative measurements of beach-litter were implemented using UNEP/MAP metadata through four years of fieldwork surveys from 2017 to 2021, for identifying their quantities, materials, and main sources to support simulation of their possible fate and trajectory.

This study concluded that 72% of beach accumulated material was artificial polymers and that variation in climatic conditions significantly influences trajectory and distribution patterns of ML under the forces of strong wind and rain fall. The most exposed sites to ML pollution were nearby public and private beaches, historical sites, Eastern and Western harbors, and Abu-Qir bay. Protection measures for vulnerable coastal locations along Alexandria Governorate are recommended.

Keywords: GNOME, plastics, marine litter, trajectory, model.

INTRODUCTION

The definition of ML includes any anthropogenic, artificial, or processed solid wastes that have been discarded, disposed of, or abandoned in the marine environment (Sheveal y, *et al*., 2012). ML poses a global multi-dimensional challenge for marine and coastal ecosystems (Pawar, 2016), polluting the world's waterways and negatively impacting vital ecological, economic and social sectors (Norden, *et al*., 2018).

Litter seriously threaten marine wildlife through different forms (i.e., entanglement, ingestion, and habitat alteration, degradation, or destruction) (UNEP, *et al*., 2012). ML consists mainly of different low-degradable materials (Allsopp, *et al*., 2006), which have been purposely discarded or brought indirectly into the sea and in beaches (Galgani, *et al*., 2015). Discarded plastics are one of the most abundant type of ML (Melanie, *et al*., 2015) that can persist for decades in the marine environment, and travel as a transboundary material (Landrigan, *et al*., 2020).

Numerical models can be utilized to simulate the movement of litter for a number of different purposes (NOAA, 2016). Ocean currents and winds could impact ML accumulation on shorelines, pathways, and fate (MERRAC, 2018). Floating litter can be transported until they sink to the seafloor, be deposited on the shore or degrade over time (Andrady, 2015), thus modeling the transport and fate of marine litter must take into account winds, ocean surface currents, and other factors including the type of litter (NOAA, 2016).

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Several researches applied GNOME software to track movement of ML and proved its capability of modeling the ML trajectory (Clarke, *et al*., 2018, Purba, *et al*., 2020, and Purba, *et al*., 2021). GNOME is characterized by relatively high precision with low computing power, especially in modelling litter transport in open oceans (Duhec, *et al*., 2015). This study aimed to explore the vulnerability of Alexandria Governorate coastal locations to ML using GNOME software by simulating ML pathways, and trajectory patterns. Impact of seasonal climatic variations on the geographic distribution of ML during the study period was taken into consideration. Quantitative measurements of macro-beach litter accumulation were developed in El-Shatby, Alexandria Governorate, through four years beach-surveys. ML amount, location, materials, and sources were analyzed to support management of vulnerable coastal locations that could be negatively affected by ML accumulation.

MATERIALS AND METHODS

Study area: El-Shatby sandy beach is about 140-meters-long and located in Alexandria Governorate between 31°12'26"N 29°54'54"E, as shown in Figure 1. This site suffers from the daily accumulation of ML from several nearby land-based sources (i.e., fishing, and touristic activities, mismanagement of solid waste, coastal urban areas, etc.), and sea-based sources (i.e., shipping activities).

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Figure (1): El-Shatby beach study site (Google earth, 3 November 2021)

El-Shatby beach is mainly considered as a touristic site and is surrounded by several adjacent vulnerable coastal locations that ML accumulation could negatively impact their economic and aesthetic values (i.e., touristic public and private beaches extended along Alexandria coastline, historical sites at the Eastern harbor of underwater heritage during the Greek and Roman periods (Hamouda, *et al*., 2021), Western harbor, Abu-Qir bay, and fishing areas).

Fieldwork data analysis: Beach samples were collected in the study as number of items per square meter from 2017 to 2021 through different seasons. A standard sampling unit of 100m stretches to the back was monitored according to UNEP/MAP metadata (Vlachogianni, 2014), taking a 30 meters shift from the beach-end to the right as a buffer, as shown in Figure (2).

Figure (2): Location of ML accumulated in El-Shatby beach (Google earth with photos taken by author, 12 June 2021)

Quantities, materials, sources, and the top five litter items of the beach macro-litter were defined. Surveys were not conducted during the year 2020 due to beach closure as one of Covid-19 national procedures.

Plastic Trajetcory Model: GNOME software (version 13.1.11) by NOAA, Response and Recovery Office and Emergency Response Department (NOAA, 2016), was developed to forecast the movement of ML that could be released from El-Shatby beach to the sea by accommodating a number of outside atmospheric and oceanic circulation models using the standard Eulerian/Lagrangian approach to simulate litter trajectory with regional physics. Simulated Lagrangian Elements (Les) are calibrated twice a day and forecasts are made for up to three days. The model duration was three days with a computational time step of five minutes.

For the overall movement extraction, u (East-West) and v (North-South) velocity components from surface currents, wind, diffusion, and other movers were combined together in each time step through a forward Euler scheme (a 1st-order Runge-Kutta method). Movers were given a point of (x, y, z, t) and returned a displacement (Δx, Δy, Δz) at t (Beegle-Krause, 2002), as shown in Equation (1).

$$\Delta x = \frac{\frac{u}{111,120} * \Delta t}{\cos(y)}, \quad \Delta y = \frac{v}{111.120} * \Delta t, \text{ and } \Delta z = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where:
$\Delta t = t - t_1$, time elapsed between time steps;
Y, latitude in radians;
111.120, number of meters/degrees of latitude (assumes 1' latitude = 1 nautical mile everywhere);
and,
(Δx, Δy), 2-D longitude and latitude displacement respectively, at the given depth layer z.

Model inputs: The input parameters were added in GNOME software to support scenarios of litter movement (i.e., variable wind, currents, amount and location of released ML, and random diffusion) according to the recent study (Purba, *et al.*, 2020), as shown in Table (1) and Figure (3). The historical meteorological data for Alexandria monthly wind speed, direction and rainfall were extracted from historical meteorological data of Alexandria Governorate during the model study period from January to December, 2021.

Table (1): Baseline parameter for GNOME simulation

No.	**Parameters**	**Spatial Resolution**	**Temporal Resolution**	**Source**
1	Variable Wind	¼ degree	3 hours	GFS
2	Current	1/12 degree	3 hours	HYCOM
3	Windage	1-3 %	-	Duhec *et al*, 2015
4	Mediterranean Map	-	-	GOODS (noaa.gov)
5	Coastline	-	-	GOODS (noaa.gov)

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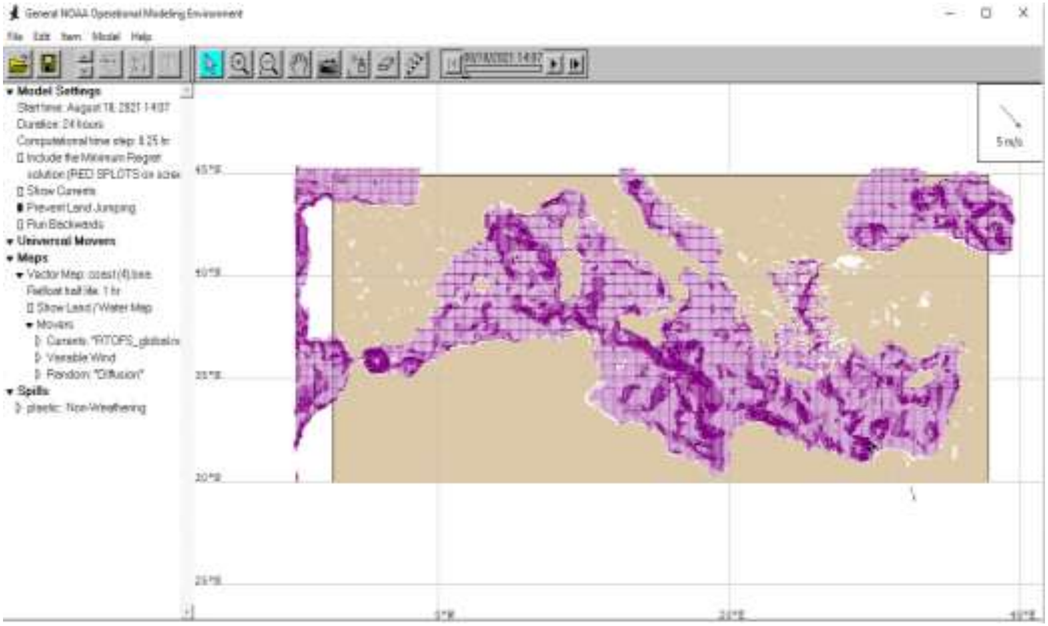

Figure (3): Modeling litter trajectory by three movers (currents, wind, and diffusion)

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Alexandria Map Extraction: File location for Mediterranean region that comprises Alexandria Governorate was extracted from GNOME Online Oceanographic Data Server (GOODS) website, as a vector map with (bna) extension, as shown in Figure (4).

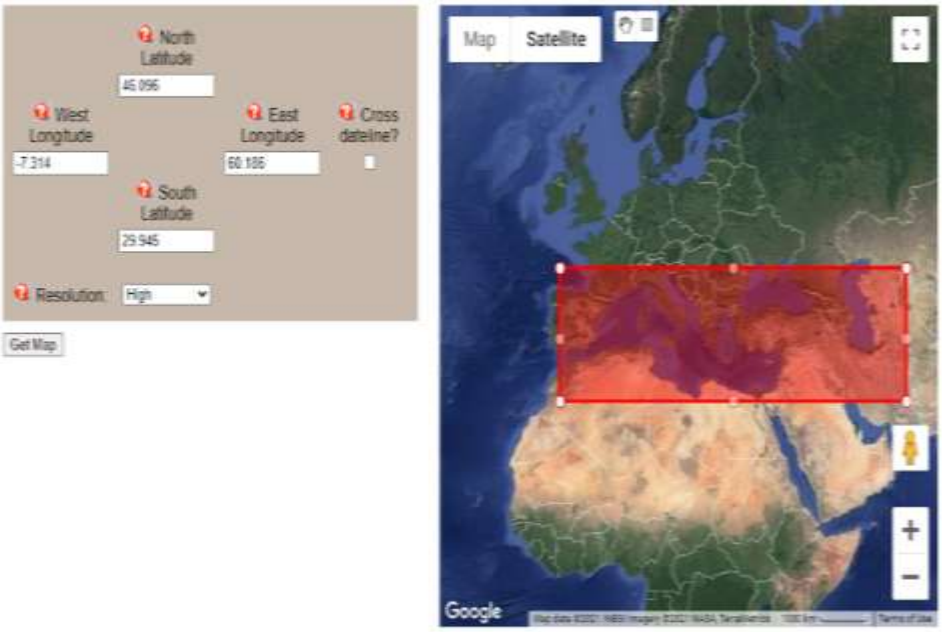

Figure (4): Mediterranean Sea location map extracted from GOODS

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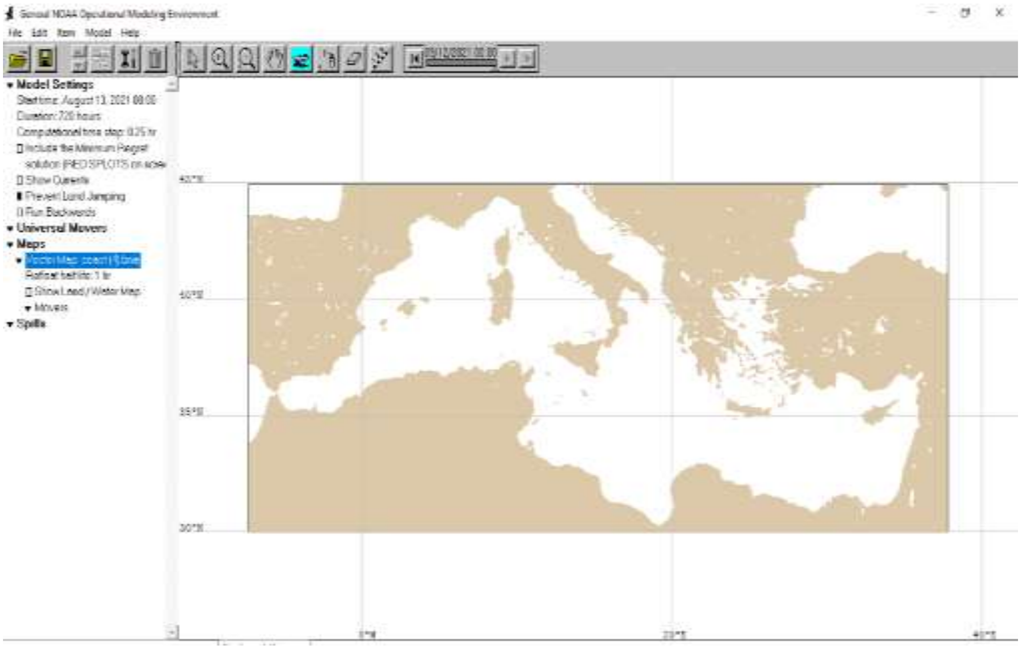

Figure (5): Location of Mediterranean region opened in GNOME model

The file location was set-up in GNOME model in a diagnostic mode, as shown in Figure (5), to customize hydrological elements for Mediterranean region (i.e., currents, wind and windage range, tides, bathymetry, boundary conditions, and shorelines), as an input data to simulate the tangible marine environment of Alexandria Governorate, where the windage range is a percentage of the wind that moves the litter.

Movers Extraction:

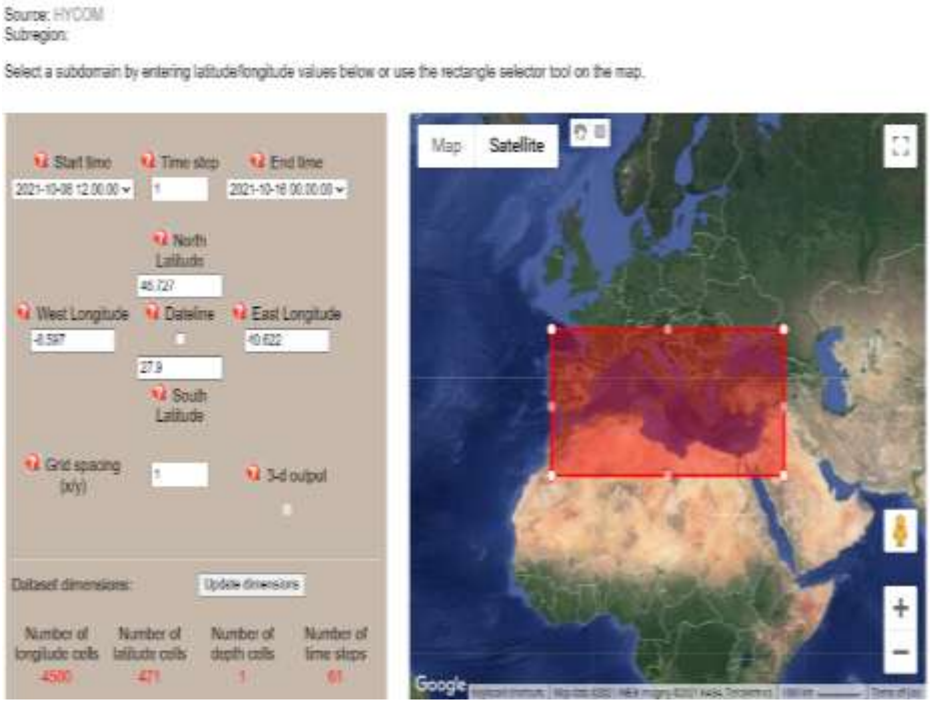

Figure (6): Current data using HYCOM extracted from GOODS

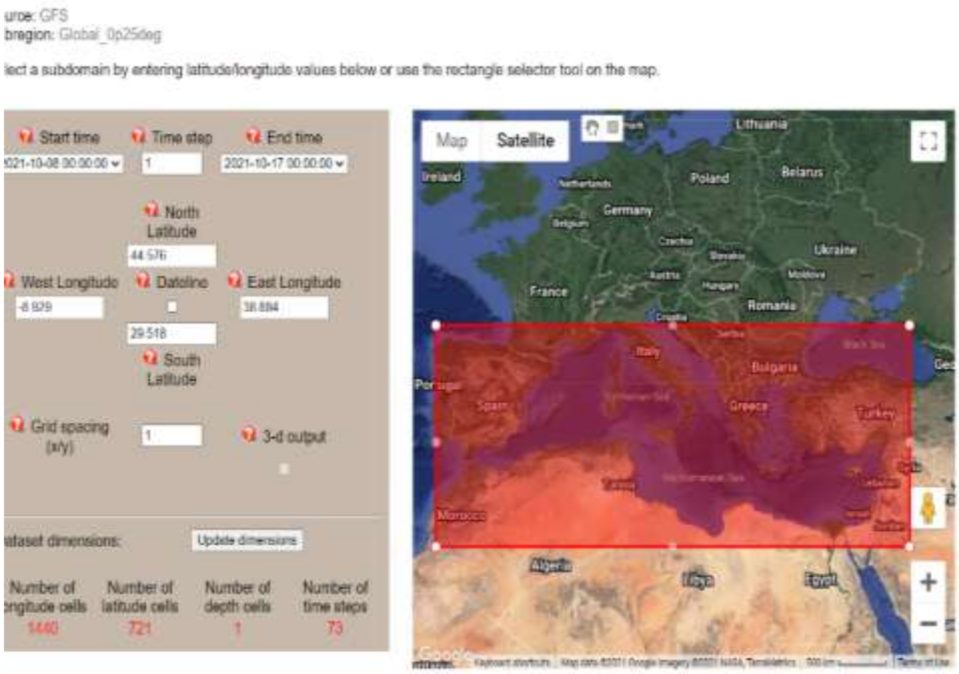

Figure (7): Wind movers at ¼ degree extracted from GOODS

Three movers of variable-wind and surface current were extracted and added to GNOME software in addition to diffusion constant, where surface current data was utilized from the 1/12° operational HYCOM (Global Hybrid Coordinate Ocean Model by the Naval Research Laboratory), as shown in Figure (6). Variable-wind data was extracted from 1/4° global wind product by the NOAA Blended Sea Winds, as shown in Figure (7).

Default model diffusion (D) constant was simulated as a random spread by a modest stochastic process with a square unit probability depending on the diffusion value that represents the horizontal eddy diffusivity within the sea water (100,000 cm^2/s). In GNOME, diffusion and spreading are treated as random processes using classical diffusion (NOAA, 2016), as in Equations (3) and (4).

$$\frac{\partial C}{\partial t} = D\nabla^2 C \qquad (3)$$

Where, C is the material concentration and D is the coefficient of the aforementioned diffusion.

$$\frac{\partial C}{\partial t} = D_x * \frac{\partial^2 C}{\partial x^2} + D_y * \frac{\partial^2 C}{\partial y^2} \qquad (4)$$

Where, D_x and D_y are the scalar diffusion coefficients in the x and y directions.

Statistical Weather Data: Alexandria Governorate is situated on the Mediterranean coast of Egypt and is generally affected by high wind speeds. According to the extracted historical data for wind conditions in Alexandria, the prevailing wind across the modelling period through 2021 was from the North-West (NW), North-North-West (NNW) and North-North-East (NNE), as shown in Figure (8).

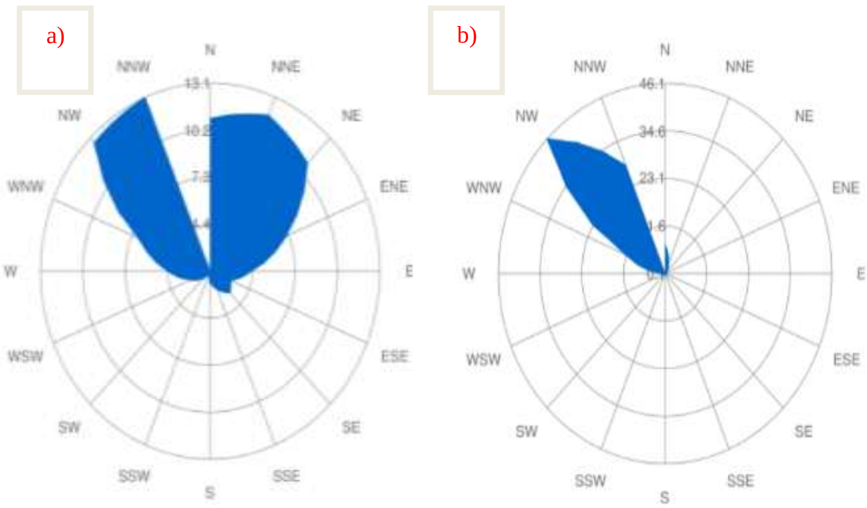

Figure (8): Average wind direction at Alexandria Governorate during (a) wet and (b) dry periods. (extracted from wisuki.com/statistics)

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Steady moderate wind was noticed in Alexandria Governorate during the warmer dry months from April to October, while the cooler wet months were from November to March.

Alexandria experienced strong winds, especially from December to February. December was the wettest month with 53.0 mm of precipitation, and August was the driest month with 0.0 mm of precipitation, as shown in Figure (9).

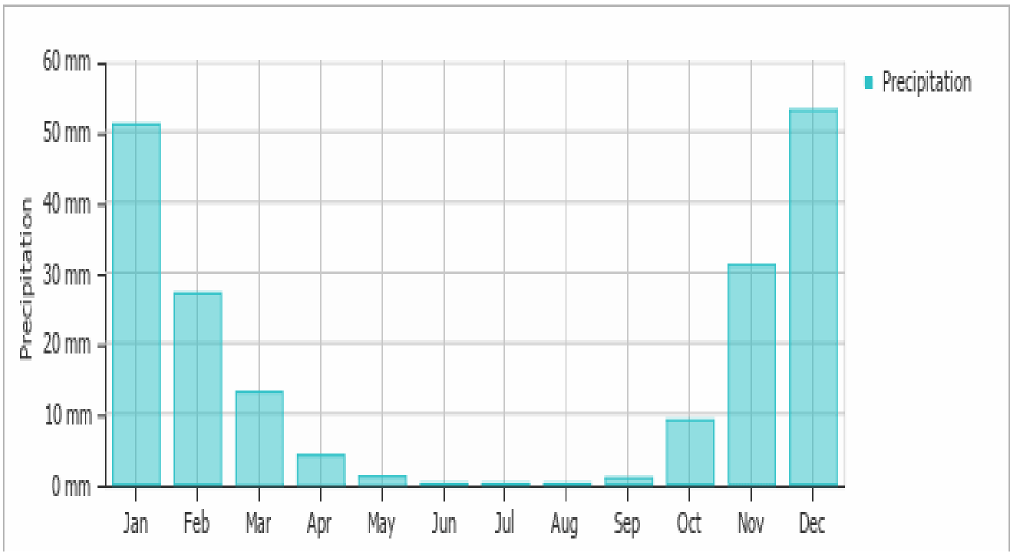

Figure (9): Average rainfall (mm) in Alexandria Governorate, Egypt (extracted from weather and climate.com)

RESULTS

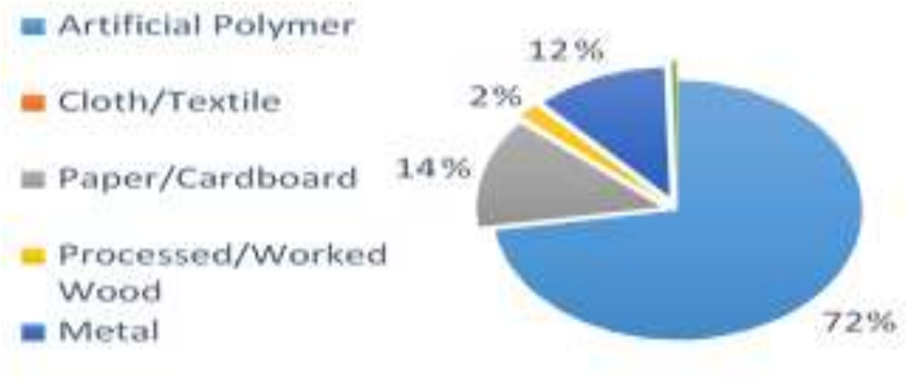

Figure (10): Identification of beach litter main materials

Field surveys showed that the maximum percentage of litter materials on El-Shatby beach were artificial polymers (72%), worked wood (2%) was the minimum, while glass/ceramics counted (0%), as shown in Figure (10).

During the study surveys the top five items were cigarette butts / filters (32%), shopping bags (28.5%), plastic caps (19.5%), metal cans (11%), and drink bottles (<=0.5l) (9%) that varied from dry and wet conditions; their weights differ from meso to macro-litter, as shown in Table (2).

Table (2): Top five items found in El-Shatby beach through surveys

Items	Materials	Polymer	Fate	Percent (%)
Cigarette butts	Polymer	Polystyrene	Sink	32
Shopping bags	Polymer	Polyethylene	Float	28.5
Plastic caps	Polymer	Polystyrene	Float	19.5
Cans	Metal	-	Sink	11
Drink bottles	Polymer	Polyethylene terephthalate	Sink	9

The majority of ML floating at the sea surface during the study period were artificial polymers (89%), where according to their specific gravity Polyethylene, Polystyrene tends to float while Polystyrene and Polyethylene terephthalate are denser than seawater and hence generally sinks towards the sea bottom (Thevenon, *et al.*, 2014).

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By comparing the average number of plastic items each year with other materials; average plastic items were about 72% of the total discarded items, as shown in Figure (11).

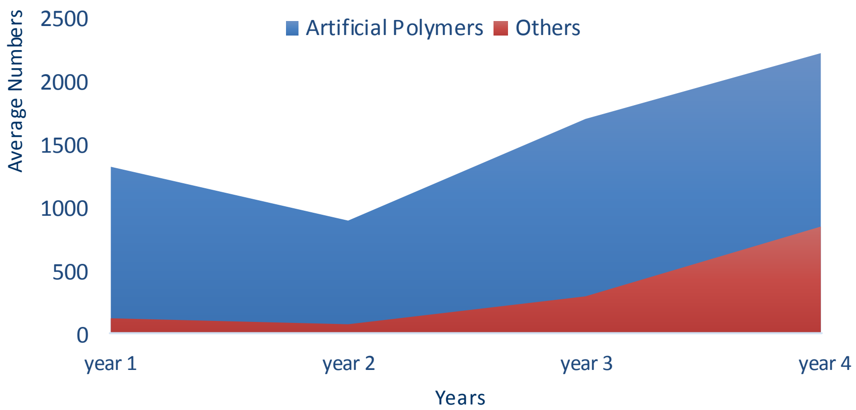


Figure (11): Artificial polymers compared with other materials

Non-weathering ML was released from El-Shatby shoreline using GNOME software. The total weight (kg) of litter items was estimated according to the fieldwork surveys to predict litter trajectory in three scenarios with different windage classes according to (Duhec, *et al*., 2015), as follows: 0–1% (low), 1–2% (medium), and 2–3% (high). The effect of wind and rainfall forces on the fate of ML was simulated to include their impact on litter movement and trajectory, Minimum regret solution (red splots) was included to consider fewer probable outcomes and uncertainties, as shown in Figure (12).

- **Dry Periods Scenario:** Litter particles were distributed along the shoreline to distances of 3.2, 5.1 km in low windage; 4.8, 16.9 km in medium windage, and 5.3, 20.9 km in high windage, at the right-side of the releasing point in best guess, regret solution respectively. In the best guess and regret solution, litter polluted the marine areas to a distance perpendicular to the shoreline of 1.1 to 2 km in low windage, 0.2 to 2.9 km in medium windage, and 0.56 km in high windage. Particles confront Abu-Qir bay and the basin of the Eastern harbor in a high windage scenario. Low windage scenarios revealed the accumulation of some litter particles in the Eastern harbor basin in both the best guess and regret solutions, and in the Western harbor breakwater in the regret solution only.
- **Wet Periods Scenario:** Most litter particles moved perpendicular to strandlines to distances of 23, 28.6 km in low windage, 14, 18 km in medium windage, and 0, 13 km in high windage in best guess and regret solutions respectively. The shoreline was strained by ML to a distance of 0,0 in low windage, and 2.6, 9.4 km in medium windage, and 8.6, 18.9 km in high windage at the right-side of the releasing point in best guess, regret solution respectively. Medium and high windage scenarios showed that the Eastern harbor basin and the breakwater of Western harbor were affected by ML pollution in regret solution, and a few particles confronted Abu-Qir bay in regret solution, high windage scenario only.

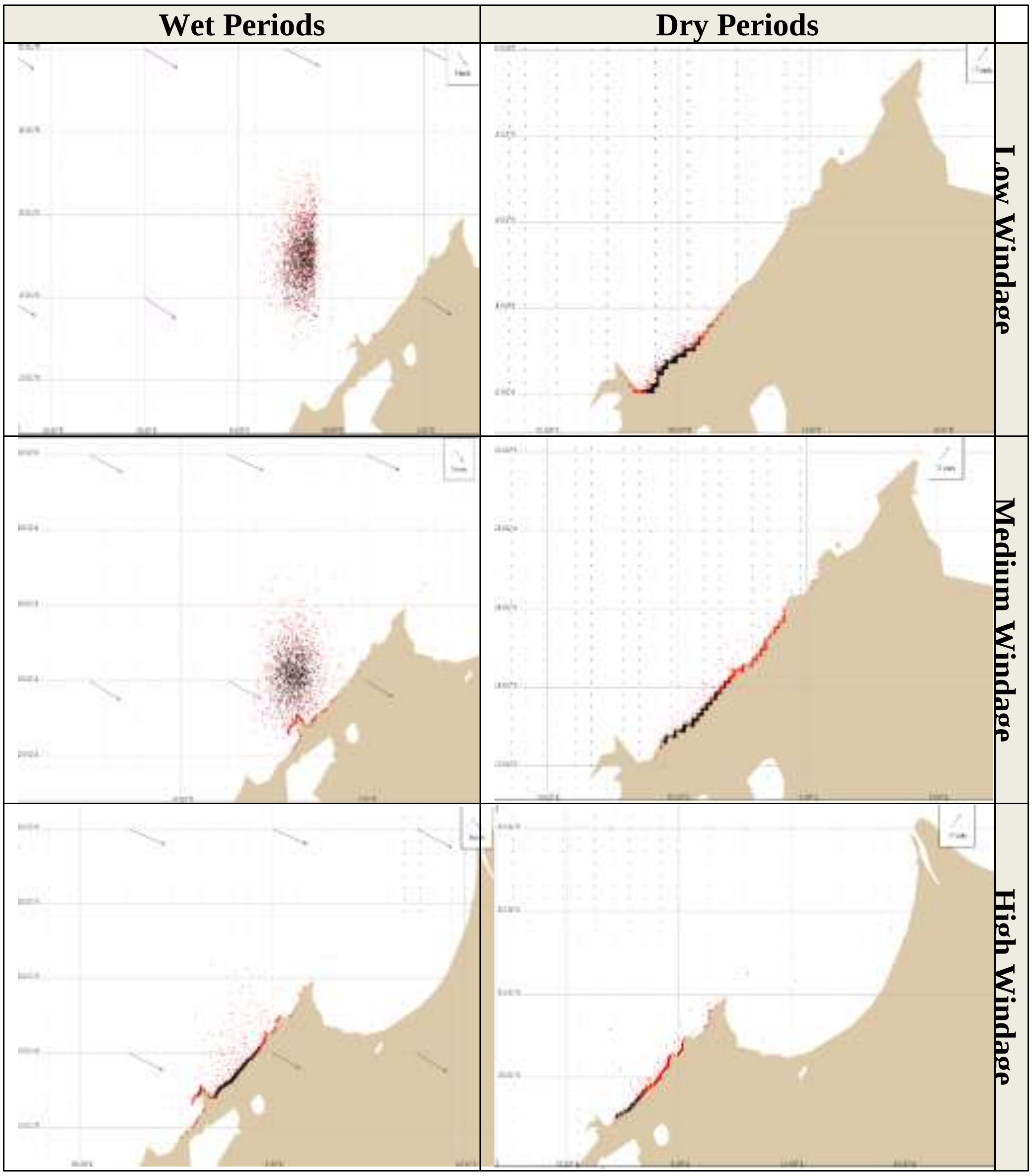


Figure (12): Scenarios of litter trajectory through different windage classes

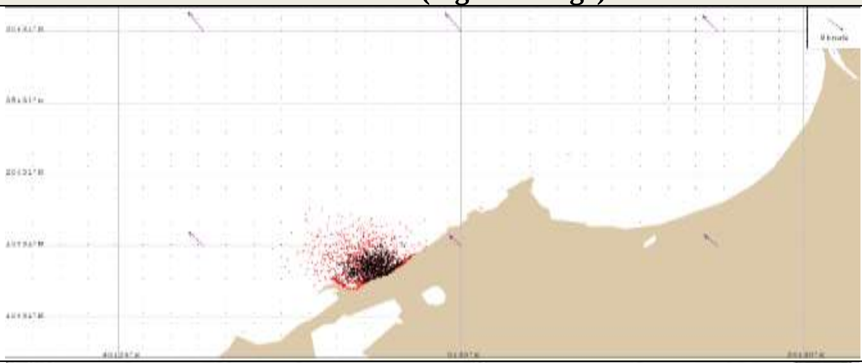
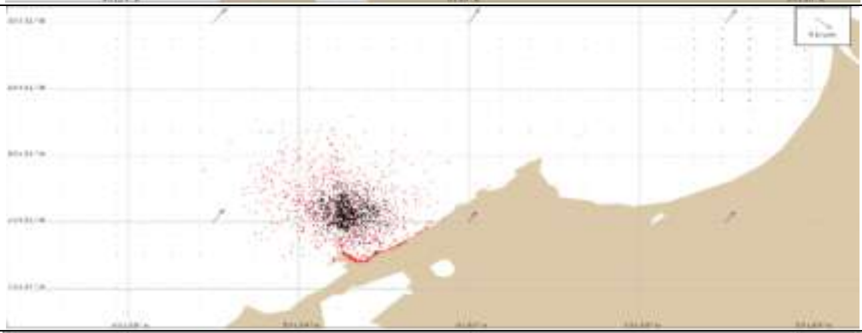
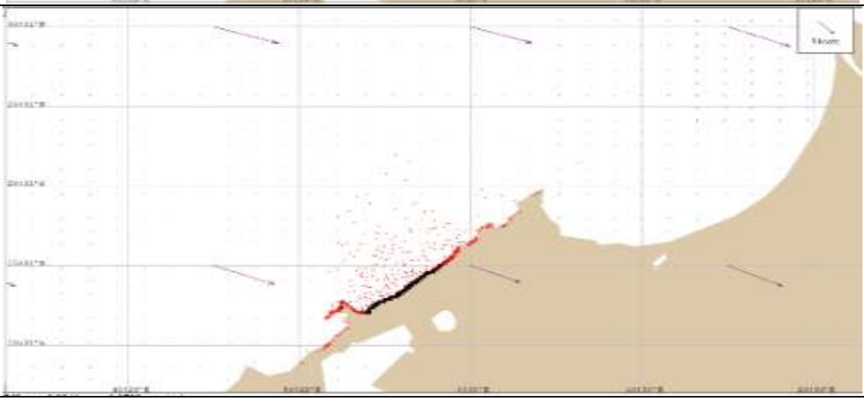
Wet Periods (high windage)	
	**First Day**
	**Second Day**
	**Third Day**

Figure (13): Tracking of litter movements in wet periods through the three days of simulation

Figure (13) clarified the difference in trajectory of ML in the high windage scenario of wet periods through three days of simulation. The litter particles settled along the shoreline on the right-side of the releasing point to a distance of 6.8, 7.8, 19.8 km, and to a distance perpendicular to shoreline of 10.9, 19.7, and 11.6 km on the first, second, and third days respectively, in regret solutions. Wet periods showed flocculation of litter movements during the three days due to variation in wind speed and strength, in addition to rainfall forces.

Figure (14) clarified the difference in trajectory of ML in the high windage scenario of dry periods through three days of simulation. The litter particles settled along the shoreline at right-side of the releasing point to a distance of 10.2, 17.8, and 20.9 km, and perpendicular to the shoreline to a distance of 4.3, 4.5, and 5.6 km, in the first, second, and third days respectively, in regret solution. Dry periods showed the accumulation of litter along the shoreline rather than in marine areas due to weaker wind speeds and the absence of rainfall forces.

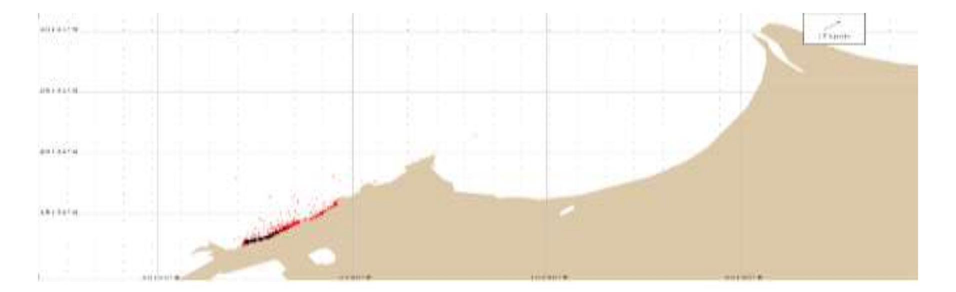
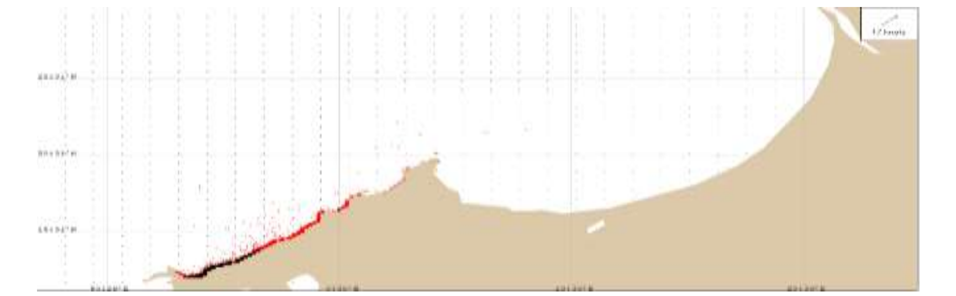
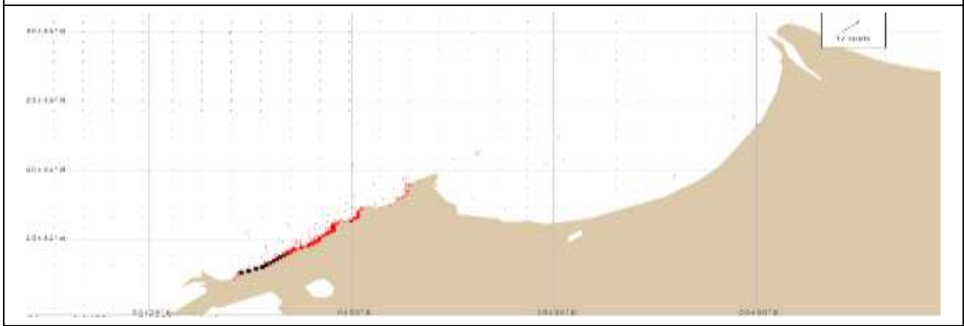
Dry Periods (high windage)	
	**First Day**
	**Second Day**
	**Third Day**

Figure (14): Tracking of litter movements in dry periods through the three days of simulation

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Backward Simulation in Dry Periods: Figure (15) showed the backward simulation developed for the dry periods, high windage scenario to examine the possible location that could transport ML to El-Shatby beach under the effect of the model movers (i.e., wind, currents, and diffusion) through three days of simulation. The results showed that ML in both regret and best guess, could be released from a location at a distance of 107 km away from El-Shatby beach on the left-side.

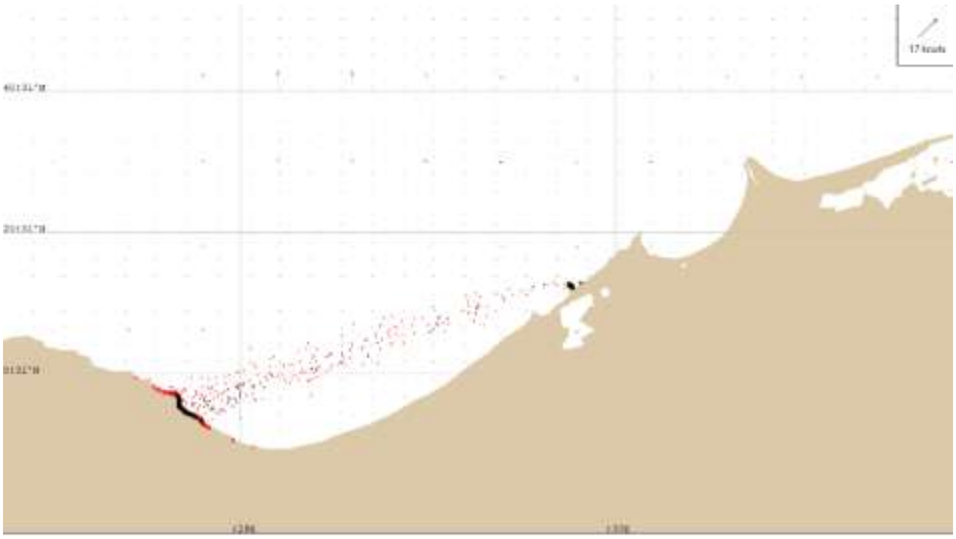

Figure (15): Backward release of ML in dry periods, high windage scenario

DISCUSSION

This study provided a scientific-based method for identifying the root-cause of litter accumulation, and understanding its possible fate and trajectory. The results of beach-surveys indicated that El-Shatby site suffered from accumulation of ML due to its location adjacent to El-Corniche, and several anthropogenic activities. Litter discard on the beach resulted mainly from land-based sources, and could be transported to the sea by wind forces. Based on previous literature, coastal tourism is considered one of the main drivers related to ML (Roddier-Quefelec, *et al*., 2020). This study also showed that the main source of discarded litter was from touristic activity while shipping, illegal dumping and fishing activities were considered as secondary sources. The results clarified that the top five items were artificial polymers, thus national effective initiatives are needed (i.e., extended producers' responsibility (EPR)).

Figure (16): Accumulation of ML at the study area of El-Shatby beach (taken by author, 12 June 2021)

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The fourth year of surveys showed increase in ML mainly resulting from domestic tourism, as locals recently preferred outdoor rather than indoor places due to Covid-19 safety measures. The results clarified that the reinforcing rocks located at the left-side of the study area, the vegetation strips distributed along the coastline, and rocks located at the backside close to El-Corniche are traps for discarded litter and fishing-nets, as shown in Figure (16). Regular clean-up of these areas could decrease the amount of litter at the study area and sea surface.

GNOME model proved that it could successfully simulate the movement of floating ML and its distribution patterns. Previous literature proved that ML has different pathways and fates of floating litter with diverse windages (Maximenkoa, *et al*., 2018). This study also verified that ML spread with different trajectories from their initial position at El-Shatby site through three windage classes (0–1% (low), 1–2% (medium), and 2–3% (high)). Wet periods showed more removal of litter particles from the strandlines, which concluded the significant impact of strong winds, and rainfall forces on the distribution pattern of ML. Dry periods showed more accumulation of ML along the shoreline of Alexandria Governorate affecting vulnerable sites.

Locations that have a great potential for litter accumulation were the public and private beaches adjacent to El-Shatby beach, basins of Western and Eastern harbors, and Abu-Qir bay. Economic and recreational activities in these locations could be negatively affected by ML. Based on previous literature, GNOME model clarified that coastal countries could suffer from ML transported from others, and at the same time could act as a source of ML (Purba, *et al*., 2021), thus backward simulation for tracking the source of releasing ML. Regular observatory system of ML could be vital to improve drift models (Maximenkoa, *et al*., 2018), at both national and regional levels. The results of this study could be considered as an important tool to support decision makers in improving collection, clean-up, safe disposal, and management practices of ML and protecting vulnerable coastal locations.

CONCLUSION

El-Shatby site, Alexandria Governorate located along the Mediterranean coast suffers from daily accumulation of ML mainly from land-based sources (i.e., touristic and fishing activities). ML increases the level of coastal and marine pollution and adversely impacts vulnerable locations and their economic and athletic values. Beach-surveys were implemented applying UNEP/MAP regional metadata, and clarified that plastics were the most polluting material accumulated at El-Shatby site. Touristic and fishing activities were the main sources of litter pollution. Litter was likely to be transported from the beach to the sea by wind forces. GNOME software proved to be a useful tool for understanding the movement and fate of ML floating at the sea surface with different windage classes. The impact of dry and wet periods on ML distribution in marine and coastal areas was simulated in this study to clarify the influence of strong winds and rainfall on ML trajectory and fate. This study could support policies for effective management of ML at national and regional levels.

RECOMMENDATION

Based on research results, a number of recommendations could be addressed for achieving a comprehensive response strategy to protect the value of coastal resources against the probability of ML accumulation, as follows:

- Monitoring of plastic litter using remote sensing techniques (i.e., Optical spectral and microwave remote sensing (SAR)) could facilitate obtaining of useful information about the existence of plastic pollution in marine and coastal areas, and effectively calibrate the results of beach-fieldwork surveys, especially in remote areas where field surveys could not be implemented.
- Protection measures for vulnerable coastal locations along Alexandria Governorate require to be considered, particularly in the locations encompassed by the minimum regret solution trajectory (red splots) as a worst-case scenario, where floating litter booms could be placed in vulnerable areas perpendicular to ML flow to create a physical barrier so floating litter could be easily captured, quantified, categorized, and disposed of safely.

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تتبع مسارات القمامة البحرية باستخدام نموذج "GNOME" على السواحل المصرية للبحر المتوسط

نهى سامي سيد[١]- علي نبيه البحراوي[٢]- حنان على فرج[٣]- نهى سمير دنيا[٤]
١) قطاع حماية الطبيعة، وزارة البيئة ٢) قسم الري والهيدروليكا، كلية هندسة، جامعة عين شمس
٣)مركز بحوث المياه ٤) كلية الدراسات والبحوث البيئية، جامعة عين شمس

المستخلص

أصبحت القمامة البحرية أحد أهم مشاكل التلوث الملحة على مستوى العالم والتي تؤثر سلبًا على المحيطات والمجاري المائية. هدفت هذه الدراسة إلى تحديد مدى تعرض المواقع الساحلية لمحافظة الإسكندرية لتراكم القمامة البحرية باستخدام برنامج الإدارة الوطنية العامة للمحيطات والغلاف الجوي للنمذجة البيئية للزيت (GNOME). تم محاكاة الالقاء الافتراضي لعدد من القمامة البحرية بشاطئ الشاطبي تحت تأثير ثلاث فئات لانحراف المواد بفعل الهواء خلال الفترات الجافة والممطرة. تم تنفيذ القياسات الكمية للقمامة البحرية باستخدام البيانات الوصفية لبرنامج الأمم المتحدة للبيئة/ خطة عمل البحر المتوسط من خلال العمل الميداني لمدة أربع سنوات من ٢٠١٧ إلى ٢٠٢١، للرصد الكمي لمؤشرات القمامة البحرية، وموادها، ومصادرها الرئيسية لدعم محاكاة المسارات المحتملة للقمامة الطافية على سطح البحر.

خلصت هذه الدراسة إلى أن ٧٢٪ من المواد المتراكمة على شاطئ الشاطبي تتكون من بوليمرات صناعية وأن الاختلاف في الظروف المناخية يؤثر بشكل كبير على أنماط مسار وتوزيع هذه القمامة تحت تأثير قوة الرياح والجريان السطحي. وتعتبر المواقع الأكثر تعرضًا للتلوث بالقمامة البحرية هي الشواطئ العامة، والخاصة، والمواقع التاريخية القريبة من الموقع، والميناء الشرقي والغربي، وخليج أبو قير. يوصي البحث بإجراءات الحماية للمواقع الساحلية الأكثر حساسية لتراكم القمامة البحرية على طول ساحل محافظة الإسكندرية.

الكلمات المفتاحية: GNOME، البلاستيك، القمامة البحرية، المسارات، النمذجة.