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Original Articles

Beach pollution from marine litter: Analysis with the DPSIR framework (driver, pressure, state, impact, response) in Tuscany, Italy

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ABSTRACT

Beaches are affected by the accumulation of natural and anthropogenic material; however, this environmental issue has not yet been explored from a One Health perspective. In this paper, the conceptual framework of DPSIR (Drivers-Pressures-State-Impact-Response) was used to understand the beach-stranded material issue in a systemic way and a data-based classification for some environmental indicators was developed to support the DPSIR analysis. The model was applied to an Italian coastal municipality as a case study, through the collection of data from a variety of data sources: publicly accessible database, data from a stakeholders' network (i.e., coastal authority, solid waste company, sewerage company, drainage consortium), and fieldwork consisting in microbiological analysis of stranded material and underlying sand, visual census of macrolitter along beach and waterways. In the study area, solid wastes production was a high pressure (768 kg/capita/year), but *in situ* visual observations of floating wastes at the outlet of the canals revealed that the contribution of local waterways to marine litter was negligible, thus suggesting the effectiveness of the measures adopted along local waterways by the drainage consortium (i.e., grids at the drainage pumping stations). Nevertheless, very high quantity of anthropogenic wastes was counted during the beach litter surveys (603 items/100 m), probably as a result of coastal current pathway that transported material from major watercourses (>100 km^2 drainage basin size; 23 items/h). On the contrary, local sewage production represented a very high pressure (>33,000 m^3/km) that impacted on the microbiological quality of the stranded material with moderate to high level of fecal bacteria indicators detected in the beach cast. The underlying sand was affected by such contamination, with most of the sample within the provisional limit set by WHO for enterococci in beach sand (60 CFU/g) that was associated to a health risk of<5 % of gastroenteritis attributable to accidental ingestion of sand; nevertheless, some enterococci peak values (980 MPN/g) could be associated to a health risk for gastroenteritis>10 %. The beach-stranded material was collected without separating the sand, with annual quantity of 1,243 kg/m, that was processed in a dedicated facility allowing to recover up to 98 % of sand and biomass after the treatment, with moderate expenditure for the coastal municipality (22 €/m). Overall, this study allowed to better figure out the cause-effect relationships underlying the accumulation of stranded material along shoreline and the effectiveness of the management practices toward beach-stranded material. Therefore, the usage of the DPSIR framework as structuring model to understand the problem of stranded material could be useful for beach managers and administrators, and its adoption within beach management programs is worth for improving beach quality.

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1. Introduction

Coastal beaches accumulate large quantities of natural material, commonly called beach cast, composed of organic biomass, which is mainly marine vegetation (seagrass and algae, named beach wrack) and residues of terrestrial plants dragged into the sea through waterways (Chubarenko et al., 2021). However, it is becoming increasingly common to find human-made material, called beach litter, entangled within the beach cast. Beach litter belongs to the global concern of marine litter, that represents one of the eleven "descriptors" of the Marine Strategy Framework Directive (MSFD) to reach the good environmental status of EU marine waters, namely the descriptor 10: "*The composition, amount and spatial distribution of litter on the coastline* […] *are at levels that do not cause harm to the coastal and marine environment*." (MSFD – Directive 2008/56/EC).

Specifically, beach litter refers to any human-made and solid material that accumulate along the coastline, which derive from a multiplicity of sources from the mainland (e.g., poorly managed landfill or wastewaters, illegal pipes) or directly produced in the marine environment (e.g., fishing, or recreational boats, aquaculture) (UNEP, 2009; Veiga et al., 2016). In recent years, the presence of beach litter has progressively increased, and is responsible for various impacts on the environment, human health, and economic activities (GESAMP, 2020). For example, litter mixed with organic biomass hampers the application of ecological management strategies of beach casts (e.g., burial, recycling) and increases the disposal or incineration of beach-stranded material as ordinary solid urban waste (Iñiguez et al. 2016) with higher economic and ecological costs. Moreover, the litter can be a vehicle for microbes adsorbed from the surrounding waters, as demonstrated for floating material (Zettler et al., 2013). For this reason, the problem of beach contamination cannot be tackled from one single perspective but needs to be regarded holistically and integrated within a One Health perspective that recognizes the complexity of the system and the environmental, economic, and societal impacts, including human health. A conceptual framework frequently used to tackle environmental problems is represented by the DPSIR (*Driving Force-Pressure-State-Impact-Response*) approach. According to the European Environment Agency's (EEA) general definition of DPSIR (Kristensen, 2004), the **driving** forces are the human needs consisting in economic and social development (e.g., population, industry, tourism), which create **pressures** on the environment (i.e., waste production, polluting emissions, land use). In turn, pressures can lead to changes in the **state** of the environment, i.e., modifications in the physical, chemical, and biological properties of the environmental matrices (air, water, and soil), which can negatively **impact** ecosystem functioning and services, as well as human health and economic activities. These impacts lead to social and political **responses** to minimize, or accommodate the environmental changes (e.g., regulations among stakeholders, public participation). Each component of the DPSIR framework is described through one or multiple environmental indicators (EEA, 1999), which provide information on the phenomena they address and could be used in relation to policymaking (Cormier et al., 2013; Lewison et al., 2016; Dzoga et al. 2020). DPSIR has been effectively applied to address various coastal issues, such as eutrophication (Cave et al., 2003; Garmendia et al., 2012), climate change (Hossain et al., 2015), ecosystem health (Xu et al., 2004; Tett et al., 2013), environmental management (Sousa et al., 2017), and plastic pollution (Abalansa et al., 2020). The aim of this work was to face the problem of the beach-stranded material from a multi-dimensional point of view, using the structured approach provided by DPSIR framework and taking an Italian coastal municipality as a case study. To support the DPSIR analysis of the phenomenon and to generalize its use to other coastal areas, we developed a classification for some key environmental indicators, that allows to better figure out the relationships among the various DPSIR components, including the effectiveness of the management practices toward beach-stranded material. To the best of our knowledge, this is the first study to apply the DPSIR framework to the contamination of beaches and to categorise the environmental indicators considered, which could also be used for the analytical interpretation of pollution issues in other beach environments.

2. Material and methods

2.1. Study area

The coastal municipality studied (Pietrasanta) is located in the north of Tuscany (Italy) and covers 42 km^2 with 4.8 kms of sandy beaches (Fig. 1). The municipality belongs to a homogeneous hydrological area, characterized by a medium–high mountain chain (Apuan Alps), which is approximately parallel to the coast and a short distance from it (around 15 kms). The drainage basin consists of a series of ditches under sea level, which are mechanically discharged by drainage pumping stations into canals above the sea level (Carducci et al. 2020). One of these canals is a natural watercourse (10.9 km length), which originates from the mountain chain of the Apuan Alps and flows directly into seawaters (named the Motrone canal in the final tract), while the other canal is a human-made ditch built to drain runoff waters (Fiumetto canal). The shoreline consists almost entirely of bathing establishments and is highly frequented by beachgoers during the summer season (June to September).

2.2. General framework

The DPSIR model was used to tackle the problem of the accumulation of beach-stranded material (hereafter stranded material) along shoreline, following the typical five-step procedure (Fig. 2). The environmental indicators have been selected from marine litter-related literature and adapted to the needs of the present investigation, as described below.

(i) Driving forces. Although the traditional definition of the DPSIR identifies drivers as deriving only from anthropogenic factors (Oesterwind et al., 2016), marine-focused studies commonly divide drivers into anthropogenic and natural ones (Atkins et al. 2011; Sousa et al., 2017), whose approach we therefore decided

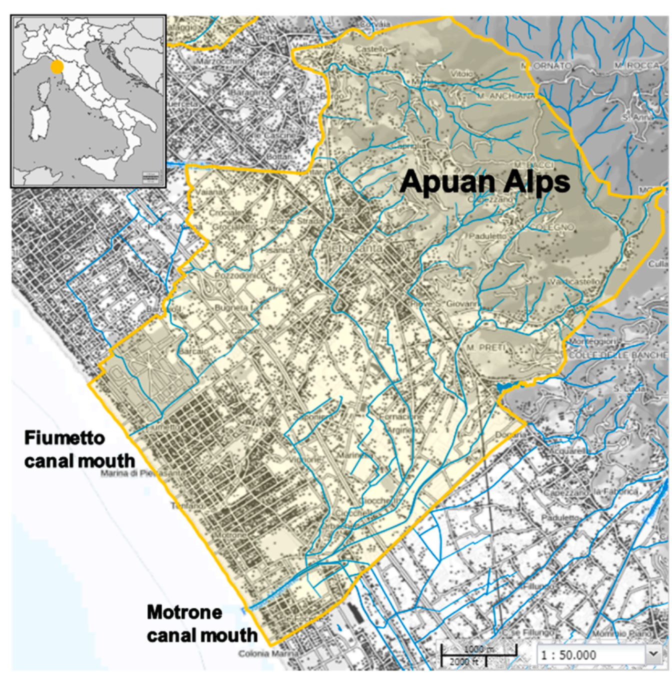

Fig. 1. Location and territorial extension of the study area (GEOscopio WMS, Tuscany Region www.regione.toscana.it/geoscopio/cartoteca).

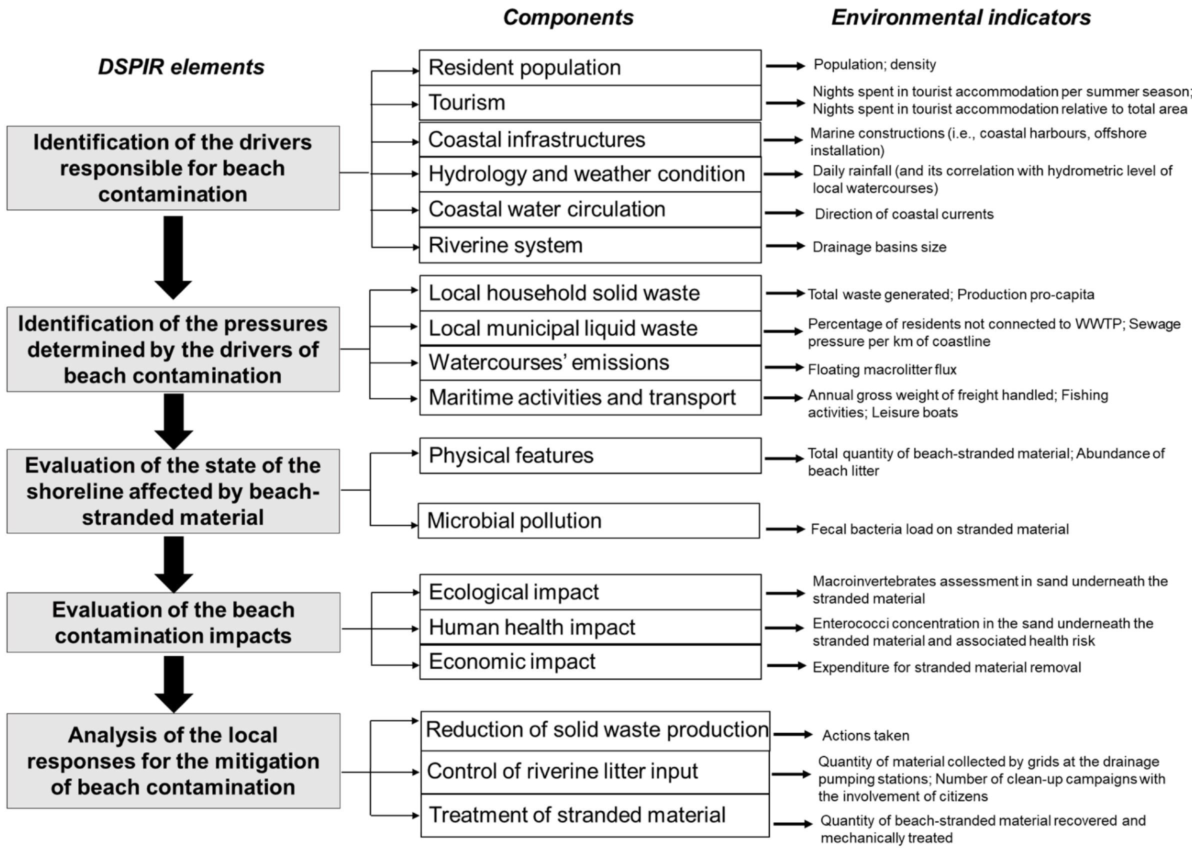

Fig. 2. Flow chart of the DPSIR application to beach-stranded material. The components of each DPSIR element are identified and the various environmental indicators are also reported.

to follow. Among the anthropogenic drivers of material accumulation, we identified the resident population, tourism, and maritime infrastructures as indicators, while natural drivers were represented by hydrology and weather conditions, coastal water circulation, and riverine systems.

(ii) Pressures. Marine pollution can have both a land- and sea-based origin, however most litter is land-based origin (approx. 80 %, United Nations, 2017). Land-based litter results from the mishandling of solid waste (i.e., accidental loss of waste from inadequately covered waste containers or from waste transport vehicles, UNEP and NOAA, 2012), or inadequately treated sewage containing sewage-related debris (e.g., tampons, contraceptives, cotton buds, Veiga et al., 2016) and fecal contamination. Therefore, as pressures, we considered emissions into the local waterways in terms of solid and liquid waste production and the riverine discharges. Among the pressures for the sea-based litter, we considered vessel traffic.

(iii) State. We evaluated the state of the stranded material in terms of the amount, type, and biological features.

(iv) Impacts. We addressed the impacts of stranded material considering its influence on the sand beneath, in terms of beach-dwelling organisms (environmental impact) and of the presence of microbes relevant for human health (health impact), and the costs associated with clean-up and treatment activities (economic impact).

(v) Responses. We investigated the adopted measures to tackle the stranded material issue, by dividing it into prevention and management activities.

2.3. Data collection and processing

The model was applied using data gathered from public data repositories and documents, a stakeholder network, and fieldwork as reported in Table 1, separately for each DPSIR element (see Table S1 for detailed description of data acquisition for each of the selected environmental indicators). The stakeholder network was set up and fieldwork was performed in the context of a project specifically aimed at investigating the problem related to beach pollution. All the collected data refers to the last five-years time frame (2017–2021).

2.3.1. Public data repositories and documents

A series of data has been collected from various agencies and institutions. Descriptive statistics for indicators of drivers and pressures were calculated using data extracted from databases of Tuscany Region, Regional Hydrological Service, Regional Waste Observatory, and Italian National Institute of Statistics. Moreover, data on the catchment area and coastal infrastructure were derived from Italian Ministry of the Environment (MATTM) and Environmental Protection Agency of Tuscany region (ARPAT) documents, respectively. Then, scientific literature has been used to fill any gaps of information.

2.3.2. Stakeholder network

The stakeholder network was composed by coastal authority, sewerage company, solid waste company, and drainage consortium. Such entities were involved in the project through interviews and sharing of their own databases, with the aim to analyse the local pressures in terms of liquid and solid waste production, the economic impact and the responses applied to tackle the problem of stranded material.

Table 1
Data sources for DPSIR framework applied to beach pollution in the study area.

DPSIR element	Public data repositories and documents			Stakeholder network		Fieldwork
	Public databases	Technical reports	Scientific literature	Private databases	Interviews	
Drivers	X	X	X			
Pressures	X	X		X		X
State				X		X
Impacts				X		X
Responses				X	X	

2.3.3. Field work

Data collection on the beach of Pietrasanta was performed from August 2020 to August 2021 with the aim to understand the role of local waterways in the accumulation of wastes along the beach, to study stranded material from an environmental and microbiological perspective and its possible health and environmental impacts. We selected three sampling sites along the shoreline to cover the study beach (one site for each watercourse mouth and one in the middle) and two monitoring stations for watercourses' observations (one for each outlet of the local drainage basin) (Fig. 1).

2.3.3.1. Visual litter census of waterways and beach, macroinvertebrates assessment. Seasonal surveys (four in total) were conducted to investigate visible anthropogenic debris (macrolitter, items with a size range of > 2.5 cm; EC JRC, 2013) along the study beach and local waterways, during storm events (Menicagli et al., 2022). For visual beach litter survey, each monitoring site consisted of a 100 m long and 20 m wide transect, parallel to the coastline, along the deposition line of the beached material (12 observations in total). Sampling was carried out through a visual census of the macro-waste found within the 100 m of beach, thus the results were expressed in items/100 m. For the surveys on litter input from waterways, observation sites were selected in proximity to the canal's outlets to account for floating macrolitter entering the sea, during a half an hour observation period (16 observations in total), and the results were expressed in items/h. To understand the possible impacts of stranded material on beach-dwelling animals, approximately-five-hundred grams of sand were sampled from areas covered and not covered by the stranded material, for each sampling location. Samples were transported to the laboratory and observed under a stereomicroscope (Leica WILD M3C, Germany) for macroinvertebrates identification.

2.3.3.2. Microbiological monitoring of beach. Monthly surveys (12 surveys in total) were performed to investigate microbial contamination of stranded material and the underlying sand. In each site, one-hundred grams of beached material and the sand beneath were collected, separately, into sterile bags and transported cold (4 °C) to the laboratory, where they were processed without oven-drying. Stranded material consisted in the beach cast that were divided into fragments<5 cm before the analysis. Samples were eluted with sterile distilled water using a 1:10 sediment-to-eluant ratio and shaken for 30 min at 100 rpm. The extraction fluid was settled for one minute and analysed using Colilert and Enterolert with Quanti-Tray (IDEXX Laboratories, Maine, USA) for the detection of total *Escherichia coli* (*E. coli*) and intestinal enterococci, respectively. The results were given in most probable number (MPN) per grams (MPN/g) (Sabino et al., 2011; Brandão et al., 2021). A total of 36 sand samples and 33 stranded material samples (on one sampling date, no material was found on the beach) were collected in the study period.

2.4. Classification of environmental indicators

Classification of some environmental indicators was developed in this paper through the analysis of data retrieved from public data repositories, namely Statistical Office of the EU (EUROSTAT; https://ec.europa.eu/eurostat), European Marine Observation and Data Network (EMODnet; https://emodnet.ec.europa.eu/en), and *RIverine and Marine floating macro litter Monitoring and Modelling of Environmental Loading* (RIMMEL). In particular, the last five-years data (2017–2021, in accordance with timeframe of the data collected for the study area, Sect. 2.3) were extracted for each indicator and a five grades classification (very low, low, middle, high, and very high) was computed using the quintile's method. Briefly, Eurostat databases were used as data sources for the classification of anthropogenic drivers and of pressures regarding wastewater treatment plant (WWTP)-related aspects and solid waste production (EUROSTAT, 2021a, EUROSTAT, 2022a, EUROSTAT, 2022b, EUROSTAT, 2022c, EUROSTAT, 2022d). Regarding sewage pressure per km of coastline (m^3/km), the obtained categories of wastewater discharges expressed in million cubic meters (m^3) (EUROSTAT, 2022b) were divided by the total length of the EU coastline (68,000 km; EEA, 2020). Monitoring data on > 2.5 cm size litter were considered in terms of floating macrolitter flux at the outlets of the main European rivers (RIMMEL database; González-Fernández et al., 2021) as well as in terms of litter abundance along the beaches (EMODnet database; IFREMER et al., 2021).

When large databases were not available, the categories were inferred using data published in scientific literature. Therefore, microbial pollution categories for the stranded material were inferred from data presented by Imamura et al. (2011) on fecal indicators in beach cast accumulated along marine beaches. The expenditure for near-shore stranded material removal was derived combining the costs reported by two studies on European beaches (Mouat et al., 2010; Mossbauer et al., 2012). The enterococci concentration in sand (MPN/g) corresponding to different levels of gastrointestinal (GI) health risk were computed using the formula provided by WHO (2021): Cs = (Cw * Vw)/Ms; where Cw is the enterococci concentration in the seawater (MPN/ml), Vw is the volume of seawater accidentally swallowed (ml), and Ms is the weight of sediment ingested (g).

For other indicators, existing classifications have been acquired from the literature. Hence, the precipitations were classified according to five daily rainfall categories based on a study on the detection of extreme precipitation time-trends in the Mediterranean region (Alpert et al. 2002). Rivers were categorized into three classes according to the size of their drainage basin, following the information provided by RIMMEL for the classification of the European rivers. Finally, the annual handling of goods by ports were classified on the basis of EU relevance, considering a recent Eurostat report (EUROSTAT, 2021b).

2.5. Data analysis

Each environmental indicator is expressed as median and interquartile range (IQR), considering the first and third quartile of the data distribution. The indicators' classifications based on international databases were derived through the calculation of percentiles 35, 55, 75, 95 taking into account all data from the timeframe (2017 – 2021). Pearson's correlation (r) was used to investigate the association between the rainfall and the hydrometric level of the Motrone canal; moreover, it was used to test the association between the two fecal indicators (*E. coli* and enterococci) in the stranded material and to understand if there were differences in each fecal indicator load between sand and stranded material. Significance level was set at p-value < 0.05. All calculations were performed with Excel for Windows (Microsoft Office Excel 2016, Redmond, Washington, USA).

3. Results

Results are structured according to each DPSIR element, and a classification of the selected environmental indicators is also included (Table 2).

3.1. Driving forces

3.1.1. Natural driving forces

Annual rainfall varied from a minimum of 939 mm/year to a maximum of 1,310 mm/year with 29 % and 34 % of rainy days, respectively. The main contribution to the annual amount of rain was provided by light and light-moderate rain categories, that represented the 80 % of the precipitation events in the 5-years study period (Figure S1). Interestingly, rainy days falling within such categories were strongly associated with an increase of the hydrometric level of the Motrone canal (Pearson correlation, $r = 0.303$, $p < 0.0001$), that could determine an increase of the quantity of terrestrial debris that reached the sea from local waterways.

The municipality coastal area is interested by two main longshore currents: one from the mouth of the Arno River flowing north, and the second one from the mouth of the Magra River flowing south. The direction of such prevalent coastal currents suggests that the shoreline may also be affected by materials coming from watercourses (as well as harbours) located within the seacoast section, that stretches for 50 kms from Magra to Arno rivers. In particular, three large rivers flow in such area (Magra, Serchio, Arno) and several small-size drainage basin rivers (Table 3).

3.1.2. Anthropogenic driving forces

The residential population was substantially stable in the last 5 years, varying from 23,121 to 23,662 inhabitants, with a very high population density (Table 3). Tourism statistics revealed that the study area received many visitors, with high number of nights spent in tourist accommodation relative to the total area (Table 3). In particular, tourist flux was concentrated during the summer (from July to September), when the population dramatically increased, with up to 60,471 tourist arrivals (visitors who stay at least one night) and a median of 6,900 nights/km^2 (Figure S2). The quality of the coastal environment may also be affected by three main coastal infrastructures: the ports of Marina di Carrara and Cinquale (approx. 30 kms and 10 kms north of the study area, respectively), and the port of Viareggio (approx. 10 kms South).

Table 2
Categories of selected environmental indicators and their references. Classification developed from databases refers to the analysis of 2017–2021 timeframe.

DPSIR component	Environmental indicator	Units	Classification	Data source
Driving forces				
Hydrology and weather condition	Daily rainfall	mm/day	Light: < 4, Light-Moderate: 4–16; Moderate-Heavy: 16–32; Heavy: 32–64; Heavy-Torrential: 64–up	Alpert et al. (2002)
Riverine systems	Drainage basins size	km^2	Small: < 100; Medium: 100 – 1,000; Large: > 1,000	RIMMEL https://mcc.jrc.ec.europa.eu/main/dev.py?N=simple&O=394&titre_chap=%C2%A0&titre_page=RIMMEL%20observation%20Network
Resident population	Density	inhabitants/km^2	Very low: < 83; Low: 83 – 105; Moderate: 105 – 137; High: 137 – 462; Very high: > 462	This paper, analysis of database (EUROSTAT, 2021a)
Tourism	Nights stayed relative to total area	nights/km^2	Very low: < 284; Low: 284 – 682; Moderate: 682 – 1,072; High: 1,072 – 2,531; Very high: ≥ 2,531	This paper, analysis of database (EUROSTAT, 2022a)
Pressures				
Local household solid waste	Production pro-capita	kg/capita/year	Very low: < 439; Low: 439 – 493; Moderate: 493 – 518; High: 518 – 791; Very High: > 791	This paper, analysis of database (EUROSTAT, 2022b)
Local municipal liquid waste	Percentage of residents not connected to WWTP	%	Very low: < 1.7; Low: 1.7 – 6.7; Moderate: 6.7 – 21.1; High: 21.1 – 84.7; Very High: > 84.7	This paper, analysis of database (EUROSTAT, 2022c)
	Sewage pressure per km of coastline	m^3/km	Low: < 2,401; Very low: 2,401 – 4,032; Moderate: 4,032 – 8,391; High: 8,391 – 33,072; Very High: > 33,072	This paper, analysis of database (EUROSTAT, 2022d)
Watercourses' emissions	Floating macrolitter flux	items/hour	Very low < 4; Low: 4 – 12; Moderate: 12 – 30; High: 30 – 140; Very high: > 140	This paper, analysis of database (González-Fernández et al., 2021)
Maritime transportation	Annual gross weight of freight handled	million tonnes/ year	Not EU relevant < 1; EU relevant: > 1	EUROSTAT (2021b)
State				
Physical features	Abundance of beach litter	items/100 *m*	Very low: < 6; Low: 6 – 88; Moderate: 88 – 338; High: 338 – 1,502; Very high: > 1,502	This paper, analysis of database (IFREMER et al., 2021)
Microbial pollution	Fecal bacteria load on stranded material	MPN/g of stranded material	Very low: < 1; Low: 1 – 10; Moderate: 10 – 100; High: 100 – 1000; Very high: > 1000	This paper, inferred from Imamura et al. (2011)
Impacts				
Human health impact	Enterococci concentration in the sand underneath the stranded material and GI health risk	MPN/g of sand	Low: 12 – 60 (risk = 1 % – 5 %); Moderate: 60 – 150 (risk = 5 % – 10 %); High: > 150 (risk = > 10 %)	This paper, following the approach by WHO (2021) for estimating the correspondence between enterococci and health risk
Economic impact	Expenditure for stranded material removal	€/m	Low: < 8; Medium: 8 – 32; High: > 32	This paper, inferred from Mouat et al., 2010 and Mossbauer et al., 2012

GI = gastrointestinal.

Table 3
Classification of the environmental indicators in the study area. Results are expressed as median values and interquartile range (IQR) in the study period (2017–2021).

	Indicators (units)	Result (median, IQR)	Classification
DRIVING FORCES	***Hydrology and weather condition***		
	Daily rainfall (mm/day)	4 (1 – 13)	Light-Moderate
	Riverine systems		
	Drainage basins size (km^2)	In the studied Municipality: Baccatoio = 28	Small
		In the seacoast nearby: Arno: 8,544; Magra: 1,685; Serchio: 1435; Carrione = 47; Ricortola = 7; Frigido = 63; Versilia = 91; Camaiore = 49	Small to Large
	Resident population		
	Density (inhabitants/km^2)	561 (558 – 562)	Very high
	Tourism		
	Nights relative to total area (nights/km^2)	835 (402 – 4164)	Moderate to High
PRESSURES	***Solid wastes production***		
	production pro-capita (kg/capita/year)	786 (761 – 804)	High to Very high
	Liquid wastes production		
	Resident population not connected to WWTP (%)	11.4 (single value)	Moderate
	Sewage pressure per km of coastline (m^3/km)	38,984 (36,834 – 39,218)	Very high
	Emission from watercourses		
	Amount of waste transported by local watercourses (item/hour)	Local waterways: 1 (0 – 4.5) during storm condition and negligible during dry weather	Very low
		Major watercourses: 23 (14 – 35) for Magra river; 4 (1 – 5) for Arno river	Moderate to High
	Maritime transportation		
	Annual gross weight of freight handled (million tonnes/year)	2.2 (0.2 – 2.7)	EU relevant port
STATE	***Physical features***		
	Abundance of beach litter (items/100 m)	603 (427 – 967)	High
	Microbial pollution		
	Microbial load on beach-stranded material (MPN/g)	*E. coli*: 12.5 (2.2–4.81 $\times 10^2$) Enterococci: 40.0 (4.1–2.91 $\times 10^2$)	Moderate to high
IMPACTS	***Human health impact***		
	Enterococci concentration in the sand underneath the stranded material and associated GI health risk	8 (2 – 25); < 5 % GI risk. Highest concentrations: 435 and 980; > 10 % GI risk	Low in 91 % of samples, high in 9 % of samples
	Economic impact		
	Expediture for stranded material removal (€/m)	22 (21 – 31)	Medium

There are no offshore installations for aquaculture, energy production, or fuel extraction in the study area.

3.2. Pressures

3.2.1. Solid and liquid wastes emissions

Household solid waste. Annually the municipality generated a large amount of household solid wastes, with a peak of around 19,200 tons/year, and consequently a very high production pro-capita (Table 3). Waste management facilities are located in neighbouring municipalities within a 10 kms distance: one for mechanical–biological and bio-stabilization processes (135,000 tons/year) and another for composting the green waste fraction (25,200 tons/year) (ATO Tuscany coast, 2019).

Municipal liquid waste. The study area hosts one WWTP with a treatment capacity of 55,000 population equivalent (P.E.), which discharges within a few kilometres from the coastline (5 kms) and to which a moderate percentage of resident population was not connected (Table 3). Based on the annual wastewater volume discharged and the length of the municipality coastline, the sewage pressure per km of coastline was very high (Table 3), with some variation attributable to the summer tourism that determined median wastewater discharges 1.5 times higher during July and August (46,525 m^3/km) compared to the rest of the year (33,058 m^3/km). The drainage basins also receive the effluents from two smaller WWTPs (5,000 P.E. and 21,000 P.E.) located in the neighbouring municipalities. Sewer overflow occurred during periods of heavy rainfall because of storm-water intrusion (Federigi et al., 2017).

3.2.2. Watercourses' outputs

Local outputs of the drainage system (Motrone and Fiumetto canals) were monitored during storm events, showing a maximum of 8 item/h enter into seawater (Table 3), while during dry weather no artificial material was individuated. The direction of the prevalent coastal currents (Section 3.1.1) suggests that the shoreline may also be affected by materials transported by three major rivers that are located approx. 30 (Magra and Serchio rivers) and 40 (Arno River) kms away from the study area. Among them, Magra and Arno rivers have been included in a pan-European project on floating litter emissions into the marine environment (RIMMEL project), showing low to moderate transport of visible items (Table 3).

3.2.3. Maritime transportation

The commercial port of Marina di Carrara is relevant at European level since it handles over one million tonnes of goods annually (Table 3), with median movements of 1 (IQR = 0.8 – 1.4) million tonnes inwards and 1.3 (IQR = 1.1 – 1.7) million tonnes outwards. Fishing traffic relies on both Marina di Carrara and Viareggio ports, with catching operations performed by small fishing vessels with an average gross tonnage (GT) per vessel of 10 GT, most of which are equipped for artisanal fishing and the rest for trawling. Overall, Viareggio port has a higher fleet capacity, with 128 fishing vessels and 1,595 GT, while Marina di Carrara has 80 vessels for a total tonnage of 83 GT. Recreational boating traffic is well developed in Viareggio and Cinquale ports, with up to 1,708 and 350 moorings, respectively. In the study area, maritime traffic may therefore be responsible mainly for lost or abandoned gear from fishing boats and litter thrown overboard by passengers from recreational boats.

3.3. State

3.3.1. Quantities of stranded material and beach litter

Field observations revealed that stranded material consisted mainly of beach cast represented by terrestrial plants, woods, and fragments of the seagrasses *Posidonia oceanica* L. Delile and *Cymodocea nodosa* Ucria Ascherson, where visible anthropogenic debris were entangled (Menicagli et al., 2022). The median weight of the removed stranded material (of both natural and anthropogenic origin) was 1,243 kg per meter beach line during a year (IQR = 1,209 kg/m/year – 1,467 kg/m/year). Such amount was collected from solid waste company without separating the sand, therefore it referred to a mixture of stranded material and sand. Field investigations revealed a high abundance of anthropic wastes with size >2.5 cm during storm events (Table 3), that was in accordance with anthropogenic litter counted along Italian coastline (Fortibuoni et al., 2021).

3.3.2. Biological pollution of stranded material

Microbiological analysis revealed similar occurrence of fecal indicators in the stranded material, slightly higher for enterococci (70 %, 23/33) compared to *E. coli*. In such matrix, the concentration of *E. coli* and enterococci were significantly correlated ($r = 0.723$, $p < 0.0001$). According to the median values of each bacterial indicator distribution load, the fecal contamination was moderate/high, with 40.1 % of the concentration values of both indicators falling in the high to very high categories of microbial pollution, namely > 100 MPN/g (Table 3).

Unlike biological agents, no field data are available on the chemicals in the stranded material. However, during the period of the fieldwork, some chemicals in the priority list of the Water Framework Directive (WFD) have been detected in seawater along three monitoring stations within 30 kms from the study area, whose concentrations exceeded the WFD thresholds, namely mercury (0.12 μg/L), nichel (2.5 μg/L), lead (0.5 μg/L), benzoapyrene (0.00027 μg/L), and tributyltin (0.0004 μg/L) (ARPAT, 2020). Therefore, chemical pollution of stranded material cannot be excluded, as a result of adsorption process of chemicals from surrounding seawaters to marine debris (Mato et al., 2001).

3.4. Impacts

3.4.1. Environmental impacts of stranded material

Laboratory evaluation on beach-dwelling animals in sand did not reveal the presence of macro-invertebrates, either in sand under the beach litter and in control samples (sand not covered by such material). Such results confirmed that intense human activities along shoreline (i.e., development of infrastructures, bathing establishments, and beachgoer frequentation) had a detrimental effect on beach ecosystem functioning, and the intense, recurrent sediment perturbations hinder the growth of a macrofauna typical of the supralittoral zone of Mediterranean sandy beaches. The loss of wildlife in the study beach hampers any assessment of the ecological impacts attributable to the stranded material. However, in beach environment similar to the study area but less transformed by humans, some field evidences throughout Europe demonstrated that organisms like the amphipod *Talitrus saltator* (Montagu, 1808) (common name: sanhopper) can ingest small anthropogenic litter, especially microplastic (items < 5 mm) while feeding on natural detritus, therefore it could be monitored as biological indicator to gain insights on the microplastic distribution in the microbiota (Morrison et al. 2017; Iannilli et al., 2019).

3.4.2. Health impacts of stranded material

Laboratory analysis showed the presence of fecal bacterial indicators in the sand underneath stranded material, with more than half of sand samples positive for fecal indicators, namely 53 % (19/36) and 61 % (22/36) for *E. coli* and enterococci, respectively. The correlation of the bacterial loads between the stranded material and the sand was statistically significant both for *E. coli* ($r = 0.723$, $p < 0.001$) and enterococci ($r = 0.582$, $p < 0.001$). However, microbial abundance was slightly lower in sand compared to the stranded material, with median values in sand samples of 4 MPN/g (IQR = 2 – 15 MPN/g) for *E. coli* and 8 MPN/g for enterococci (IQR = 2 – 25 MPN/g). Therefore, our fieldwork results suggested the protective role of stranded material on the microbial pollution of the underlying sand, probably protecting them from the environmental conditions (e.g., sunlight irradiation, desiccation) that normally reduce the microbial load on the sand surface (Whitman et al., 2014). Regarding health risk associated to accidental ingestion of sand, WHO recently released a provisional threshold value for enterococci of 60 CFU per gram of sand, that was associated to a GI health risk of 5 %, namely-five cases of gastroenteritis in 100 exposures to the contaminated sand. Most of the sand samples had values of enterococci<60 MPN/g (91 %), thus revealing a low risk of gastroenteritis for beachgoers; however, two samples showed concentrations up to 980 MPN/g, that correspond to a high GI risk (Table 3). Health impacts of stranded material could derive also from the chemicals acquired from seawater and then transferred to the sand (i.e., polycyclic aromatic hydrocarbons). Information on chemicals accumulation in stranded material is widely underexplored and limited to plastic resin pellets (small 10 – 50 mm granules; Takada et al. 2012). Moreover, the studies on human health risk from exposure to chemical-contaminated sand are limited to beaches impacted by oil spills (Black et al. 2016; Altomare et al., 2021), therefore after the occurrence of extreme contamination events.

3.4.3. Economic costs

In the study area, the economic impact included the removal of stranded material from nearshore beach and their treatment in a dedicated facility (Sect. 3.5.3). The annual expenditure for this service had a median value of 109,600 € (IQR = 107,209 €/year – 153,293 €/year). Considering the length of the coastline (5 kms), operation of collection and processing of stranded material were associated to a moderate cost (Table 3), with a maximum of 41 € per meter of beach. Nevertheless, if we consider the quantity of stranded material (median of 1,243 kg/m/year, Sect. 3.3.1), the cost is 21 € per ton of processed beach cast, that is 8 times lower compared to the costs reported by Mouat et al (2010) and Mossbauer et al. (2012) for stranded material management along UK and Germany seacoast, respectively.

3.5. Local responses

3.5.1. Reduction of solid waste production

Starting from 2012, the coastal authority and the solid waste company improved the Technical Specification for Waste Management, with the adoption of a door-to-door separate collection system. Although the result of such policy in reducing waste disposal was clearly evident (Table 4), the real effectiveness in reducing anthropogenic waste along shoreline is difficult to quantify, as commonly happen during the evaluation of marine litter policies (Morseletto, 2020). In addition, in summer 2019, the coastal authority limited the use of disposable plastic products (e.g., cutlery, plates, glasses) on beaches, thus introducing a policy in line with the European law on the banning of single-use plastic items in the market (Directive EU 2019/904). The bathing establishments replaced plastic products for food purposes with biodegradable ones and installed dedicated bins whose content was sent to the composting plant (Sect. 3.2.1). The result of this policy was not quantifiable, because the garbage collected in bathing establishments' bins were aggregated with household wastes, thus hampering the estimation of the amount of recycled wastes.

3.5.2. Control of the riverine litter input

The drainage consortium coordinated various actions along the drainage basin to retain anthropogenic and natural debris and consequently to prevent their entry into seawater, both technical

Table 4
Results of the responses and their effect in reducing the accumulation of material along shoreline.

Responses	Outcome	Effect of the outcome in reducing beach-stranded material
Prevention actions toward stranded material		
Improvement of specification for solid waste management	Recycled waste increased from 8,785 tons/year (44.2 %) to 15,053 tons/ year (81.3 %).	Not measurable
Banning of single-use plastic items from bathing establishments	Not quantifiable (garbage from the bins were aggregated with the household wastes)	Not measurable
Drainage pumping stations equipped with grids	Collection of 7.5 tons/year from the Motrone canal	Negligible transport of floating macrolitter from the local waterways
Management actions toward stranded material		
Stranded material treatment	Treatment of stranded material allowed annual recovery of sand and natural biomass, ranging between 47 % – 59 % and 25 % – 38 %, respectively.	Removal of stranded material, from a minimum of 563 tons/year to a maximum of 2,660 tons/ year

interventions and activities with the engagement of citizens.

3.5.2.1. Technical measures. Technical measures consist in grids installed in the drainage pumping stations which retain the medium to large size wastes, to prevent them from interfering with the mechanical operation of the pumps. Moreover, floating barriers are placed in proximity to the two local canals' mouths to stop wastes from the drainage system. Annual quantity of material entrapped in the drainage grids were available (Table 4) and the absence of floating macrolitter at the canal's outlets (observed during fieldwork) suggested the effectiveness of the technical measures along local waterways.

3.5.2.2. Citizen engagement. Drainage consortium involved groups of citizens for watercourses clean-up events in the spring and autumn, before the maintenance work on the canal banks takes place. Such campaigns are important opportunity for citizen engagement and increasing of environmental awareness, but the lack of registered information on the amount (weight) and types (e.g., plastic, glass) of collected waste hamper the evaluation of the real contribution of such events in reducing pollution.

3.5.3. *Stranded material treatment*

The study area has a specific stranded material management practice, represented by a facility for the mechanical treatment of stranded material (7,000 tons/year). Once the material from beach cleaning has been collected (a mixture of stranded material and beach sand), a mechanical vehicle equipped with grids (8 mm square mesh) removes the trapped sand, which can be used for beach nourishment plans. The residual material is manually sorted on a conveyor belt, in order to separate the green fraction from the anthropogenic waste. The recovered green fraction is then sent to a composting plant located in the neighbouring municipality (Sect. 3.2.1). The anthropogenic material is recovered from plastic, wood, and glass, while the unsorted material is landfilled (Fig. 3). In the 5-years study period, the facility recovered approximately half of the total weight of the treated material of sand (51 %; 3,729 tons) followed by organic green fraction (31 %; 2,248 tons), while the anthropogenic waste represented only 3 % (213 tons); the remaining 15 % weight-loss was attributable to evaporation (Table 4).

4. Discussion

Throughout the world, the beaches are interested by the accumulation of natural material, residues of either marine vegetation (seagrass, algae) or terrestrial plants, increasingly containing anthropogenic debris. Nevertheless, legislative frameworks on stranded material often consider natural and human-made components, separately. As an example, the MSFD focus exclusively on anthropogenic component, and recently set a limit of 20 items/m calculated on the basis of the baseline contamination of the European coastline, owing to the paucity of scientific data on harms caused by marine litter on beaches (Van Loon et al., 2020).

Undoubtedly, anthropogenic content of stranded material represents an environmental problem, owing to deleterious effects on organisms living on beaches, both vertebrates (e.g., birds; Kühn et al., 2015) and macroinvertebrates (Poeta et al., 2015) as well as on plant growth in dune systems (Menicagli et al., 2019). Moreover, beach litter-related injuries (i.e., punctures, loss of balance) represent a threat to public health (Campbell et al. 2016, Campbell et al., 2019). Nevertheless,

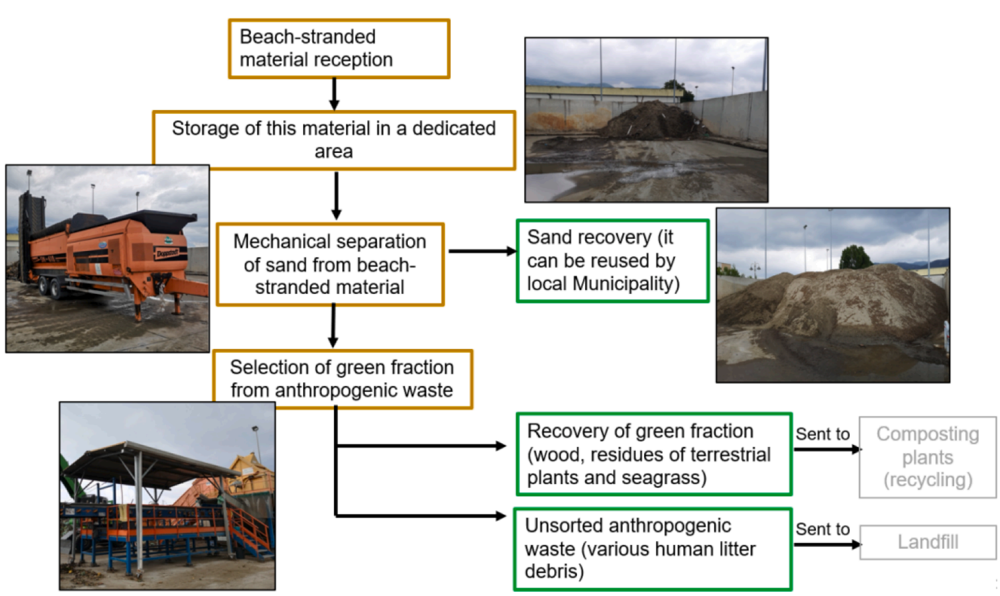

Fig. 3. Workflow of the beach-stranded material treatment facility.

health effects can derive not only from physical but also microbiological hazards, and some studies reveal that natural part of the beach cast can provide a protected environment for infectious microbes in the sand beneath (Imamura et al., 2011; Quilliam et al., 2014), thus allowing their transfer to humans through the exposure to sand mixed with the stranded material. In this regard, WHO recommend evaluating both "*programmes for litter or solid waste disposal*" and "*presence of beach wrack and seaweed, including seasonal variation*" during sanitary survey on beaches, since accumulation of wrack and the inadequate solid waste practices could contribute to microbial contamination of beach sand (WHO, 2021).

Furthermore, stranded material as a whole is also a specific economic problem for local coastal municipalities: when mixed human and natural materials strand onto the shoreline, they are legally categorized as waste once humans collect it (EU, 2000), but to date very limited research has been conducted into the costs of stranded material removal and treatment (Mouat et al., 2010; Mossbauer et al., 2012).

To make up for the lack of a holistic and systemic view of the stranded material issue, we addressed the problem considering its multiple dimensions through the structured approach provided by DPSIR framework. The application of DPSIR to a real case study allowed us to point out cause-effect relationships and the strengths and/or limitations in the prevention and management of the problem. Moreover, the classification that has been developed for some environmental indicators represents an useful instrument for the DPSIR analysis.

In the study area, solid wastes production is a high pressure, but *in situ* visual observations of floating waste at the outlet of the canals revealed that the contribution of local waterways to marine litter was very low, also during storm events when rainfall was associated to an increase of hydrometric level of the watercourses. Such a result could suggest the effectiveness of the measures adopted along local waterways by the drainage consortium (i.e., grids at the drainage pumping stations). Nevertheless, very high quantity of anthropogenic wastes was counted during the beach litter surveys and information on coastal current pathway can help in interpreting such field data. In fact, the study area lies in middle of northward and southward currents, thus it could receive wastes from approximately 50 kms coastline, where some pressures are located, namely several watercourses (from small to high drainage basins size) and some touristic and commercial ports. On the contrary, local liquid waste production represented a very high pressure that impacted on the microbiological quality of the stranded material, since we found moderate to high level of fecal bacteria indicators in the beach cast during the microbiological monitoring. Such fecal contamination was preserved also in the sand underneath the stranded material. During summer, the stranded material is periodically removed by the staff of the bathing establishments. Therefore, in the hypothetical scenario of accidental ingestion of the underlying sand, the health risk for gastroenteritis could sometimes be high, namely $>$10 illnesses per 100 exposed beachgoers.

Finally, the treatment of stranded material was a control measure perfectly in line with waste management policy recommended by the EU waste law (EU, 2008), where the recycling processes are a priority. The quantity of waste disposal was around 2 %, while all the other material was recovered as sand and biomass. The expenditure for such service was quite cost-intensive, given the huge amount of stranded material collected and processed.

Overall, the DPSIR analysis applied to this real case study showed that the problem of stranded material can be efficiently tackled at local scale, through the adoption of measures aimed at preventing floating macrolitter emissions from local waterways and the sustainable management of the stranded material. However, local riverine discharges represent a fecal pollution source, especially along heavily populated and urbanized coastal areas, and their role in the contamination of the stranded material should not be neglected in a public health perspective. Despite that, the problem of stranded material needs to be tackled in an integrated way, especially regarding material of anthropogenic origin that could derive from areas that are relatively far, as a result of coastal current pathway.

5. Conclusions

Although accumulation of material along shoreline is a growing issue in coastal environments, a systemic vision of the problem is currently missing, and data related to beach contamination are often heterogeneous and fragmented. The application of the DPSIR model using data derived from a variety of sources and fieldwork provided an integrated and holistic interpretation of the phenomenon, that could be useful for the development of beach management programs. In fact, decision making on beach environment can benefit from the understanding of cause-effect chain between the determinants and the impacts of stranded material as well as from the evaluation of the adopted prevention and management practices. However, the concrete adoption of DPSIR framework needs that it is periodically updated through the consultations among stakeholders (not only policymakers but also other local stakeholders and citizens) for a continuous improvement of beach quality.

CRediT authorship contribution statement

Ileana Federigi: Methodology, Investigation, Writing – original draft. **Elena Balestri:** Investigation, Writing – review & editing. **Alberto Castelli:** Writing – review & editing. **Davide De Battisti:** Writing – review & editing. **Ferruccio Maltagliati:** Writing – review & editing. **Virginia Menicagli:** Writing – review & editing. **Marco Verani:** Writing – review & editing. **Claudio Lardicci:** Investigation, Writing – review & editing. **Annalaura Carducci:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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