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RESEARCH ARTICLE

Multicriteria GIS-based analysis for the evaluation of the vulnerability of the marine environment in the Gulf of Trieste (north-eastern Adriatic Sea) for sustainable blue economy and maritime spatial planning

Mariangela Pagano[1,2] | Michele Fernetti[3] | Martina Busetti[1] | Mounir Ghribi[1] | Angelo Camerlenghi[1]

[1]National Institute of Oceanography and Applied Geophysics - OGS, Trieste, Italy

[2]Department of Mathematics and Geosciences, University of Trieste, Trieste, Italy

[3]GeoLab—Department of Mathematics and Geosciences, University of Trieste, Trieste, Italy

Correspondence
Martina Busetti
Email: mbusetti@ogs.it

Handling Editor: Robert Fish

Abstract

1. The Gulf of Trieste, is a shallow semi-enclosed sea of about 500 km^2 in the north-eastern part of the Adriatic Sea. The coastal and marine areas of the Italian region Friuli Venezia Giulia, which borders most of the Gulf of Trieste, are subject to significant pressure from human activities, especially in terms of maritime traffic, ports, industry, fishing and tourism. But they are also characterised by natural areas of high environmental value. We wanted to understand the human impact on these coastal and marine areas in order to better inform sustainable management.
2. To carry out the analysis, we collected a range of anthropogenic (human) and environmental data, from which we produced a series of indicator maps. By combining the various indicators, we created two subsequent maps: the seabed vulnerability map and the marine environment vulnerability map in the area as a whole. The analysis has highlighted areas with different degrees of environmental vulnerability due to human development and identified the most critical areas in the Gulf of Trieste with high anthropogenic pressure. Both maps show that human impacts affect large areas of the seabed and marine environment, while those with minimal or non-existent impacts are very limited and are related mainly to areas with high levels of existing protection and conservation.
3. The seabed vulnerability map shows that the biggest problems are related to discharge of dredging sludge, mollusc fishing with dredgers and turbo blowers, and anchoring boats. Furthermore, the presence of anthropogenic elements on the seabed can damage the natural environment and even permanently alter the natural shape and structure of the seabed. The marine environment vulnerability map shows that ports, urbanisation, industrial activities, maritime traffic and fishing pressure affect the entire study area.

4. The vulnerability maps are a useful analytical tool to identify the most critical areas where possible actions can be planned to maintain a healthy and sustainable productive marine environment and to manage and resolve the conflicts between economic development and environmental health.

KEYWORDS
Adriatic Sea, Gulf of Trieste, multicriteria Geographic Information System-based analysis, protected areas, vulnerability of the marine environment, vulnerability of the sea bed

1 | INTRODUCTION

Human pressures on the oceans and seas have increased significantly in recent decades, threatening their health and the enormous socio-economic potential and, thus, the services that the sea can provide, causing environmental, economic and social damage.

In addition to land-use change, which is estimated to affect at least 75% of land areas (Venter et al., 2016), the marine domain is also under anthropogenic pressure, leaving only ~13% of the ocean in wilderness, mostly on the high seas (Jones et al., 2018), with the Mediterranean Sea being one of the areas in the world subject to very high impact due to human activities (Halpern et al., 2015).

The European Commission considers healthy seas and oceans and productive ecosystems to be very important, providing the basis of the blue economy, the long-term strategy for developing sustainable economy in the marine and maritime sectors. The use of seas and oceans for economic activities brings benefits if the impact on marine ecosystems can be minimised. If their protection fails, not only is the economic potential of the blue economy undermined but the resources that seas and oceans provide and the functions they are capable of performing are also threatened.

In this context, two European directives are of fundamental importance: the Marine Strategy Framework Directive (MSFD) 2008/56/EC and the Maritime Spatial Planning Directive (MSPD) 2014/89/EU. The main objective of the MSFD 2014/89/EU is to protect, safeguard and restore the marine environment in order to preserve the diversity and vitality of the sea, including the seabed, and to keep it healthy, clean and productive.

The MSPD 2014/89/EU establishes a framework for maritime spatial planning (MSP), a process whereby human activities in marine areas are analysed and organised in order to achieve ecological, economic and social objectives; it consists in planning when and where human activities take place at sea to ensure that they are efficient and sustainable. Member states have to develop the mapping of these activities through maritime spatial management plans to promote sustainable growth, also promoting stakeholder participation and cooperation with neighbouring countries. MSP is a decisive tool for implementing the blue economy, facilitating sustainable development and investment in maritime activities, promoting a sustainable maritime economy, sustainable development of marine areas and sustainable use of marine resources. It ensures the protection of the marine and coastal environment through the application of the ecosystem approach, considering the strengthening of cross-border cooperation and land-sea interactions.

High-quality and easily accessible marine data are a prerequisite for sustainable economic development and the implementation of MSP. The European Marine Observation and Data Network (EMODnet) is a network of organisations supported by the EU Integrated Maritime Policy, that work together to observe the sea, process data according to international standards and make this information freely available by building an online European database on marine knowledge. EMODnet provides access to European marine data and thus a data collection that includes the Adriatic Sea.

The European Strategy for the Adriatic-Ionian Region (EUSAIR) was jointly developed in 2014 by the Commission and the countries and stakeholders of the Adriatic-Ionian Region, who agreed to work together in areas of common interest for the benefit of each country and the whole region.

The participating countries of the EUSAIR have agreed on areas of common interest with high relevance for the countries of the Adriatic-Ionian region, being it common challenges or opportunities. The aim of the countries is to create synergies and promote coordination between all territories in the Adriatic-Ionian region in the four thematic areas/pillar. Blue growth is one of the four pillars.

The ADRiatic Ionian Maritime space PLANning (ADRIPLAN) project was funded to gather knowledge and practical experience in the implementation of MSP in the Adriatic-Ionian macro-region, outlined by EUSAIR, in particular for the Adriatic Sea. The aim of ADRIPLAN is the implementation of the MSP and the opportunities for the "blue growth" of the Adriatic-Ionian macro-region. Considering in particular the Focus Area 1 (Northern Adriatic) of the ADRIPLAN project, to which the study area belongs, the main environmental issues concern biodiversity and endemic hot spots, the high risk of introduction of non-indigenous species due to the intensive activities in the ports of the northern Adriatic, the high exploitation of shellfish and fish stocks, the risk of eutrophication (contributions of the Po River and coastal lagoons), the integrity of the seabed, the high degree of coastal anthropisation and the high vulnerability to erosion and subsidence, the risk of contamination by dangerous substances (Barbanti et al., 2015).

Within the framework of the MSP, in order to assess the pressures and impacts of human activities on the key environmental components of the marine ecosystem, specific data must be collected and used, in accordance with the spatial and temporal extent of the maritime space affected by the activities. As the intensity of pressures and impacts of maritime activities on the environment is linked to the specific characteristics of the areas involved, the specific physiographic, bathymetric, oceanographic and biological characteristics of the basin should be considered as key elements, require for the to correct design and assessment of possible interventions.

There are several approaches in the scientific literature that aim to assess anthropisation in sensitive environments. The management of coastal seas and wetlands is very complex in developed countries, as they are usually exposed to intense human activities that alter the balance of the ecosystem. All these interrelated elements are often difficult to analyse comprehensively due to their diffuse nature.

The marine environments have suffered from a lack of quantitative methods to delineate areas that are sensitive or vulnerable to particular stresses, natural and anthropogenic. Zacharias and Gregr (2005) define sensitivity as the degree to which marine features respond to stresses, which are deviations of environmental conditions beyond he expected range, and vulnerability as the probability that a feature will be exposed to a stress to which it is sensitive. The concepts of sensitivity and vulnerability can be used as criteria (along with representativeness and uniqueness) in identifying vulnerable marine areas requiring special management or protection, so that these areas can be predicted and mapped.

Geographic Information System (GIS) is a very useful diagnostic tool for environmental and territorial decision-making processes. García-Ayllón (2018) proposes a methodology based on GIS analysis for the evaluation of diffuse anthropisation associated with tourism in sensitive coastal environments, by using different indicators of territorial transformation. The approach was applied to the lagoon of the Mar Menor, which is an international and successful case study for environmental recovery on the Spanish Mediterranean coast. The concept of the Socio-Ecological System to diagnose and achieve sustainable cohabitation between human anthropisation and the natural values, based on the tool of GIS participatory mapping, between public and private stakeholders in combination with economic tools such as the Willingness to Pay and the Cost Transfer Sector, is proposed as an innovative approach for the management and recovery of these complex areas (García-Ayllón, 2019).

The construction and use of decision support systems (DSSs) as combinations of decision support tools (DSTs), such as multicriteria decision analysis (MCDA) methods integrated with a GIS, is more likely to produce high-quality results for decision-makers, handle the uncertainty of analysis, and extend the long-term applicability of tools employed by coastal managers (Barzehkar et al., 2021). The effectiveness of a DSS can be increased if accurate data at a small grid cell scale is included into a vulnerability analysis, as experts are then more likely to be able to accurately identify the spatial distribution of vulnerability at the local scale (Mullick et al., 2019).

GIS is a powerful DST for storing, displaying and analysing spatial data (Iyalomhe et al., 2013), including large amounts of coastal data (Rangel-Buitrago et al., 2020) from various sources. Its usefulness in decision-making can be further enhanced by integrating MCDA methods into mathematical operations to determine priorities by assigning values and weights to maps (Malczewski & Rinner, 2015).

Different methods have been applied to evaluate anthropisation in the sensitive areas of the Adriatic Sea.

The Cumulative Impact assessment for the MSP for the Adriatic and Ionian Region was calculated according to the method proposed by Halpern et al. (2008) and Andersen et al. (2013) and using a 1 × 1 km grid, revealed that the northern Adriatic Sea, and especially the Gulf of Trieste, are among the most impacted areas (Gissi et al., 2017).

Manea et al. (2019) propose an operational approach that includes novel spatial analysis in the marine domain to quantify and map the supporting ecosystem services (ES) of the Adriatic Sea. Supporting ES provision in the Adriatic Sea was quantified through the use of indicators that denote ES delivery and that are specifically related to the three marine domains (sea surface, water column, seabed) considered separately. They identified areas of elevated provisioning levels of multiple supporting ES in the Adriatic, which is hypothesised to be priority areas of conservation.

Furlan et al. (2020) developed a GIS-based Bayesian Network for the Adriatic Sea to assess the probability, and associated uncertainty, of cumulative impacts under four 'what-if' scenarios representing different marine management options and climate conditions. An integrated approach to MSP is required, combining more sustainable management options for marine spaces and resources with climate adaptation strategies. This approach would allow to reduce human pressures on the marine environment and increase the resilience of natural ecosystems to climatic and human-induced disturbances, with an overall reduction of cumulative impacts.

The aim of this work is to assess anthropogenic pressure in the Gulf of Trieste, located in the north-eastern Adriatic Sea, by identifying weighted human and environmental indicators. This is done using the multicriteria analysis evaluation integrated in a GIS with a high resolution of 50 × 50 m grid.

2 | MATERIALS

The study area is the Gulf of Trieste, a semi-enclosed shallow sea basin, with an area of about 500 km^2, located in the north-easternmost part of the Adriatic Sea.

In the northern part of the gulf the coasts are characterised by beaches of fine or pebbly sand. In the eastern part, the coast is rocky, with narrow, pebbly and gravelly beaches (Brambati & Catani, 1988). The coastal area near Trieste has been heavily modified by anthropogenic interventions that have altered both the natural coastline and the seabed. The southern part has rocky coasts at the foot of abrasion escarpments, with several bays, such as those of Koper and Muggia.

The seabed of the Gulf of Trieste has a gentle, generally homogeneous morphology, with a maximum depth of about 25 m (Trobec et al., 2018), and a fairly uniform distribution of biocenosis, with the exception of elevations on a rocky substrate, the so-called "trezze" (Gordini et al., 2012).

The coastal and marine areas of the Gulf of Trieste are subject to considerable pressure from human activities, in particular maritime traffic, ports, industry, fishing and tourism, but they are also characterised by natural areas of high environmental value (ARPA FVG, 2014a).

Environmental and anthropogenic data from the institutional open access database were used in the multicriteria analysis evaluation to assess anthropogenic pressures. The data used in this study come from the following sources:

- Regional Infrastructure for Environmental and Territorial Data of Friuli Venezia Giulia (IRDAT FVG), which makes accessible geographical and environmental data of different origins, contents and formats produced in the region by public and private entities with the aim of supporting knowledge processes and environmental and territorial policies;
- ADRIPLAN, a project funded by the Directorate-General for the Sea (Maritime Affairs and Fisheries) of the European Commission, for the implementation of the MSP and the "blue growth" opportunities for of the Adriatic-Ionian macro-region, with a duration of 18 months (10 December 2013–10 June 2015);
- Regional Agency for the Protection of the Environment of Friuli Venezia Giulia (ARPA FVG), for the monitoring and control of the environment, research and technical-scientific support activities, and the provision of analytical services important for both the environment and health;
- Ministry of Environment, Land and Marine Protection (MATTM) responsible for carrying out the functions and duties of the State in the field of environmental and territorial protection in accordance with international directives on territorial organisation taking into account environmental values;
- OpenStreetMap, a collaborative project to create open access maps and cartography of the world, through a worldwide collection of geographical data. Anyone can contribute by enriching or correcting the data. The maps are created based on data obtained from portable GPS devices, aerial photographs and other free sources. Both the rendered images and vector data, and the geodatabase itself are published under the Open Database Licence.

2.1 | Environmental data

The environmental data have been divided by theme into 'Protected natural areas', that includes areas at European, national (Italy) and regional (Friuli Venezia Giulia) levels of protection, and 'Biological data', that include the ecological and chemical status of transitional and marine—coastal waters and the mollusc farming classification.

2.1.1 | Protected natural areas

Friuli Venezia Giulia is a region with great biodiversity and very different natural landscapes, from marine/lagoon to alpine environments. The diversity of species living in the region reflects this heterogeneity and creates a unique heritage protected by a large network of protected natural areas (ARPA FVG, 2013a).

The protected natural areas (Figure 1) in the study area are:

- Natura 2000 sites for the protection of habitats and significant animal and plant species at European level, including Sites of Community Importance (SIC, Habitats Directive 92/43/EEC) and Special Protection Areas (SPAs, Birds Directive 2009/147/EC): Grado and Marano Lagoon, Cavanata Valley and Mula of Muggia Bank, Mouth of Isonzo River and Cona Island (SIC and SPAs); Lignano Pine Grove, Cavana of Monfalcone, Mouth of the Timavo, Duino Cliffs, Trezze San Pietro and Bardelli, Wrecks of Posidonia at Grado (SIC), (ARPA FVG, 2013b);
- Ramsar sites, according to the Ramsar Convention on Wetlands of international importance, especially as waterfowl habitat, signed in 1971: Marano Lagoon—Stella Mouths, Cavanata Valley, Mouth of the Isonzo River and Cona Island, Secolje Salt-pans (Slovenia) (ARPA FVG, 2013c);
- Regional Natural Reserves: Stella Mouths which includes part of the Marano Lagoon, and the Cavanata Valley, Isonzo Mouth and the Duino Cliffs Natural Reserve which are located along the coast and include marine areas (Regione FVG, 2021);
- Miramare Marine Protected Area, part of the MAB UNESCO World Biosphere Reserve network, ASPIM Protected Area, and Natura 2000 SIC IT3340007 according to Directive 92/43/EC (Regione FVG, 2017).

2.1.2 | Biological data

Ecological and chemical status of transitional and marine-coastal (TraC) waters

In order to classify the quality of surface water bodies, ecological and chemical status must be defined, in accordance with Legislative Decree 152/2006 and the Water Framework Directive.

The ecological status refers to the quality of the ecosystems structure and functioning and is determined by assessing chemical elements (pollutants in water and sediments), physico-chemical elements (nutrients, oxygen, salinity, temperature and transparency), biological elements (BQEs) and parameters related to morphological conditions and tidal regime.

The chemical status is determined by the presence of "priority" substances, defined by EU and national standards, with concentrations above the threshold values for water, sediments and biological organisms (Distretto Idrografico delle Alpi Orientali, 2014).

The marine coastal and transitional waters of Friuli Venezia Giulia have been classified in 38 significant water bodies: 19

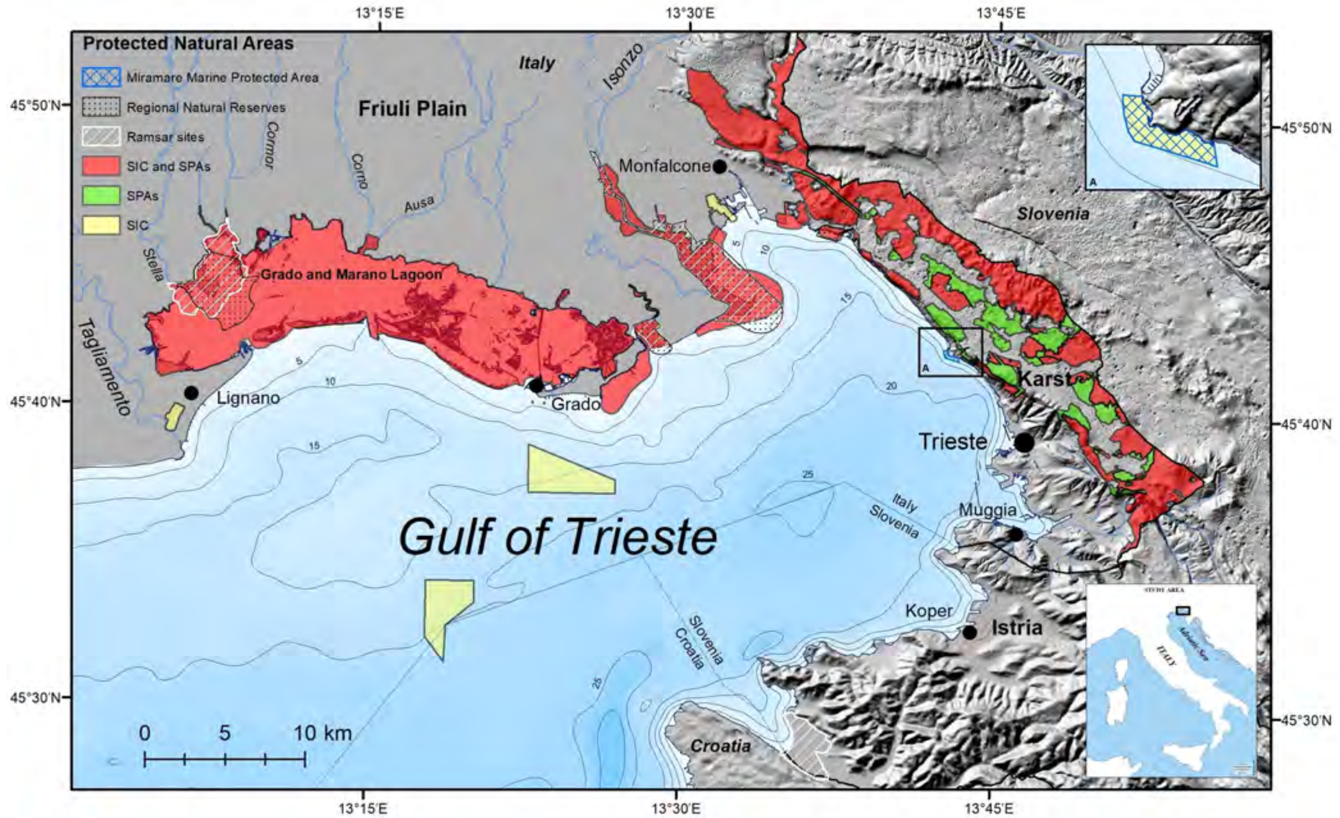

FIGURE 1 Protected natural areas in the Gulf of Trieste and in the surrounding onshore areas: Sites of Community Importance (SIC), Special Protection Areas (SPAs), Regional Natural Reserves and Miramare Marine Protected Area (see inset for details), (from IRDAT FVG, 2017) and Ramsar Sites (from ADRIPLAN, 2017). DEM compiled for Italy (from IRDAT FVG, 2017), Slovenia (from Arso, 2017) and Istria (from EU-DEM, 2017). Map compiled by using ArcGis® by ESRI software; datum WGS84, projection UTM33. Bathymetry by Zampa (2020) by using grids from Italy and Slovenia (from Trobec et al., 2018) and Croatia (from EMODnet Digital Bathymetry, 2018): contour lines in metres.

marine-coastal waters (12 coastal waters within 3000 m and 7 others up to one nautical mile from the baseline), 19 transitional waters (17 in the Grado and Marano Lagoon, and 2 located at the Isonzo and Tagliamento river mouths) (ARPA FVG, 2020) (Figure 2a,b).

The definition of ecological status was mainly based on the analysis of the BQEs macrophytes (which integrates the two elements of biological quality macroalgae and phanerogams) and benthic invertebrates, and the other elements required by the directive.

To determine the chemical status, the following priority substances were analysed: alachlor, cyclodiene pesticides, anthracene, atrazine, benzene, cadmium and compounds, chlorphenvinfos, chlorpyrifos, total ddt, ddt pp, 1,2-dichloroethane, dichloromethane, diphenyl ether bromate, hexachlorobenzene, hexachlorobutadiene, hexachlorocyclohexane, fluorocyclohexane benzo (b+j) fluoranthene + benzo (k) fluoranthene, indeno (1,2,3-cd) pyrene + benzo (g, h, i) perylene, mercury and compounds, naphthalene, nickel, nonylphenol, octylphenol, pentachlorobenzene, pentachlorophenol, lead, simazine, carbon tetrachloride, tetrachlorethylene, trichlorethylene, compounds of tributyltin (as cation), trichlorobenzene, trichloromethane and trifluralin.

The results obtained for the transitional waters show a worse ecological status than for the marine-coastal area. In particular, in the more confined areas of the Marano and Grado lagoons, the quality is poor, due to the significant contribution of fresh water rich in salts nutrients, associated with greater confinement and residence time of the water masses. These characteristics produce, in certain periods of the year, under-saturation and sporadic enrichments of the chlorophyll content.

In terms of the chemical status, mercury levels exceed the limits of the environmental quality standard in all water bodies. The main source of mercury is solid contributions carried by the Isonzo River and coming from the mining area of Idrija (Slovenia) where cinnabar has been exploited for more than 500 years. The secondary source is the spills of industrial waste from the Torviscosa chemical plant factory which has mainly compromised the area of the mouth of the Aussa-Corno river (Distretto Idrografico delle Alpi Orientali, 2014).

Classification of mollusc farming

In Friuli Venezia Giulia, two species of edible lamellibranch molluscs are bred: the mussels (Mytilus galloprovincialis) are farmed in the areas of Trieste, Duino-Aurisina and Muggia, anchored to ropes and

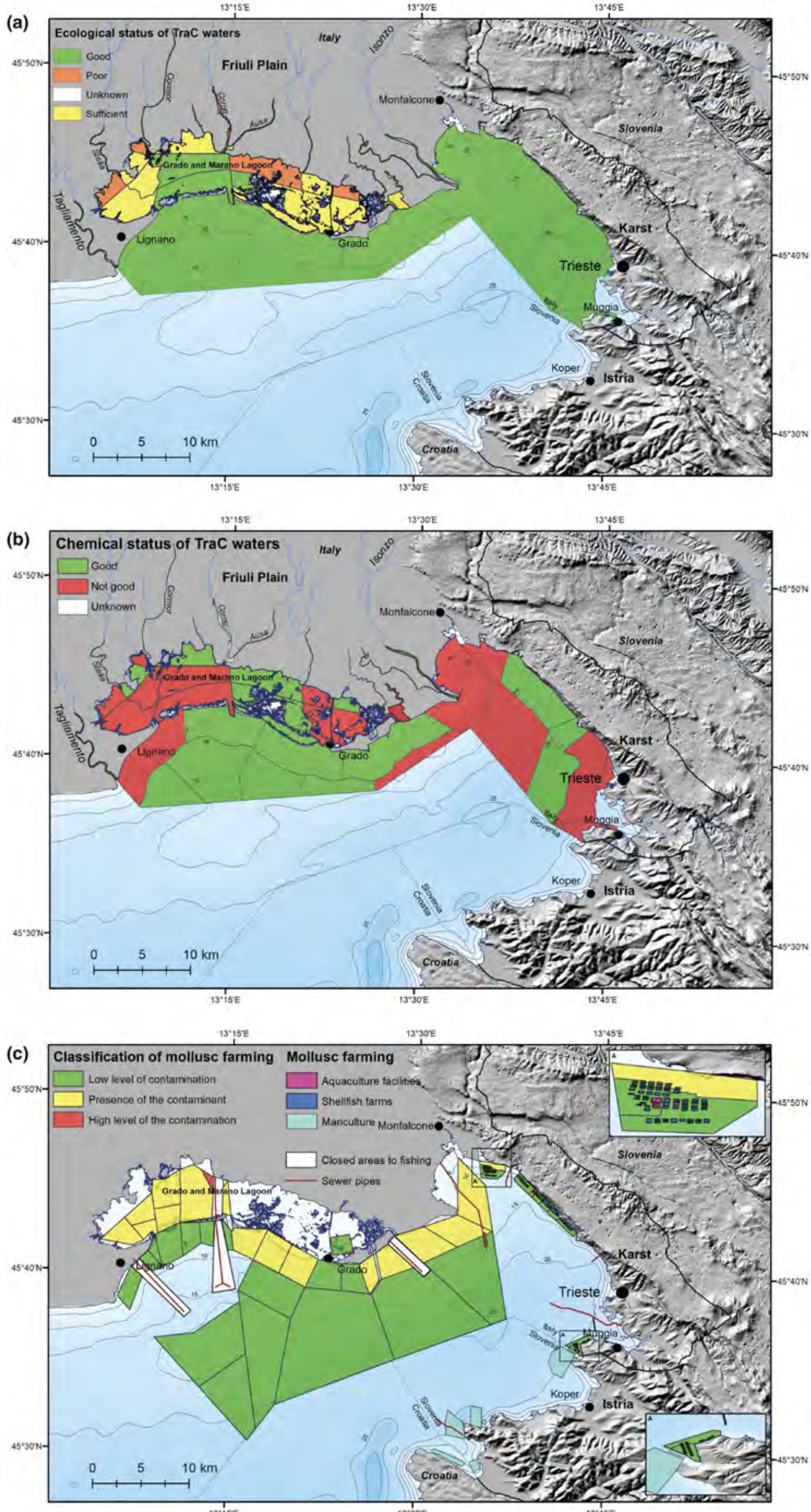
(a)
Ecological status of TraC waters
Good
Poor
Unknown
Sufficient
Italy
Isonzo
Friuli Plain
Monfalcone
Slovenia
Grado and Marano Lagoon
Tagliamento
Lignano
Grado
Karst
Trieste
Muggia
Koper
Istria
Croatia
0 5 10 km
13°15'E
13°30'E
13°45'E
45°50'N
45°40'N
45°30'N
(b)
Chemical status of TraC waters
Good
Not good
Unknown
Italy
Isonzo
Friuli Plain
Monfalcone
Slovenia
Grado and Marano Lagoon
Tagliamento
Lignano
Grado
Karst
Trieste
Muggia
Koper
Istria
Croatia
0 5 10 km
(c)
Classification of mollusc farming
Low level of contamination
Presence of the contaminant
High level of the contamination
Mollusc farming
Aquaculture facilities
Shellfish farms
Mariculture
Monfalcone
Closed areas to fishing
Sewer pipes
Slovenia
Grado and Marano Lagoon
Lignano
Grado
Karst
Trieste
Muggia
Koper
Istria
Croatia
0 5 10 km

FIGURE 2 Biological data characterisation of the Gulf of Trieste. (a) Represents the ecological status of TRAc waters (from IRDAT FVG, 2017); (b) represents the chemical status of TRAc waters (from IRDAT FVG, 2017); (c) represents the aquaculture areas and the classification of contaminant in mollusc farming (from ARPA FVG, 2017); Sewer pipes, (from the Charter Official State Nautical n.39, published by the Hydrographic Institute of the Italian Navy). Zone a: low level of contamination. Zone b: presence of the contaminants. Zone c: presence of high level of the contaminants. If the microbiological levels are exceeded (attachment A of DGR 2557/2015), collection is suspended and the area is temporarily declassified. The possible contamination of molluscs by metals is also monitored every 6 months (ARPA FVG, 2017).

nets suspended from floating buoys; the clams (Tapes philippinarum) are farmed in the areas of Marano Lagunare and Lignano Sabbiadoro and collected by fishing boats equipped with hydraulic dredges and turbo-blowers. In the natural mollusc banks of the marine waters of Monfalcone, Grado and Lignano Sabbiadoro, clams (Chamalea gallina), *capalunghe* (Ensis spp.) and *fasolari* (Callista chione) are collected with turbo blowers.

The Resolution of the Regional Council of the FVG n° 816/2016 determines that the monitoring has to be carried out for health checks in the collection, production and relaying areas of live bivalve molluscs.

The analysis of the microbiological quality of the areas where the molluscs are collected or bred, aims to classify these areas into three levels of possible microbiological contamination (Figure 2c).

2.2 | Anthropic activities

Along the coastal area there are important industrial sites, port centres, significant urban settlements (Trieste, Monfalcone, Muggia, Grado and Lignano) and seaside tourist centres. In general, 60% of the coast is used for seaside tourism, 10% for shellfish farming and the remaining 30% for different uses (ports, etc.) (Piccinetti et al., 2012).

Coastal areas are therefore subject to considerable pressure from the resident population. Tourism is undoubtedly an important economic resource for the area, but it is also another source of pressure on the environment, as it leads to an increase in waste production, traffic and consequently noise and atmospheric emissions.

2.2.1 | Port activities

Along the coastal area there are two seaports of international relevance of Trieste and Monfalcone, the smaller port area of Porto Nogaro and minor sea and river ports, docks and marinas (Figure 3a).

The Port of Trieste is an important international hub in the dynamic trade with Central and Eastern Europe and is the first port in Italy in terms of total tonnage and rail traffic, as well as the first oil port in the Mediterranean Sea (Table 1). The Port of Monfalcone is the northernmost port on the Adriatic Sea and the closest to the centre of Europe. It boasts the primacy in Italy in the sector of handling of forest products (Table 1).

Maritime transport and ports are fundamental for economic development but at the same time they cause significant environmental impacts.

2.2.2 | Industrial settlements

In the coastal area, and in particular at the two main ports of Trieste and Monfalcone, some of the most important industrial areas in the region have developed, in some cases characterised by particularly critical production activities (e.g. storage and handling of oil products, metal processing, production of plastics) in terms of potential environment impacts (ARPA FVG, 2014b).

The industrial area of Trieste is located in the south-eastern part of the region, between the port area of the city and the border with Slovenia. Monfalcone has been an industrial town for at least a century.

The industrial area of Aussa-Corno is located in the southern Friulian Plain, which is of considerable environmental interest, due to the presence of highly vulnerable biotopes, such as the Marano and Grado Lagoon, the resurgence system and the river drainage system. This area also includes the port of Porto Nogaro.

Areas where the qualitative characteristics of the soil, surface and groundwater are altered and the contaminant concentrations exceed the legal limits, due to human activities carried out or in progress, are identified as Sites of National Interest (SNI) by the Italian legislation. In Friuli Venezia Giulia, there are two SNI: the Trieste SNI and the Caffaro di Torviscosa SNI (former Grado and Marano Lagoon SNI) (Figure 3b).

Italian legislation obliges those responsible for contamination to remediate and safeguard contaminated areas, in accordance with the European principle of “Polluter Pays Principle” (ARPA FVG, 2015).

2.2.3 | Nitrate vulnerable zones from agricultural sources

The Nitrates Directive 91/676/EEC concerns the protection of waters against pollution caused by nitrates from agricultural sources. It designates nitrate vulnerable zones when nitrate concentrations exceed 50 mg/L in surface or underground freshwater or when conditions of eutrophication of the water occur.

The Marano and Grado Lagoon is exposed to different pressures related to the river contributions and anthropogenic (Figure 3b). Therefore, the lagoon environment is exposed to different levels

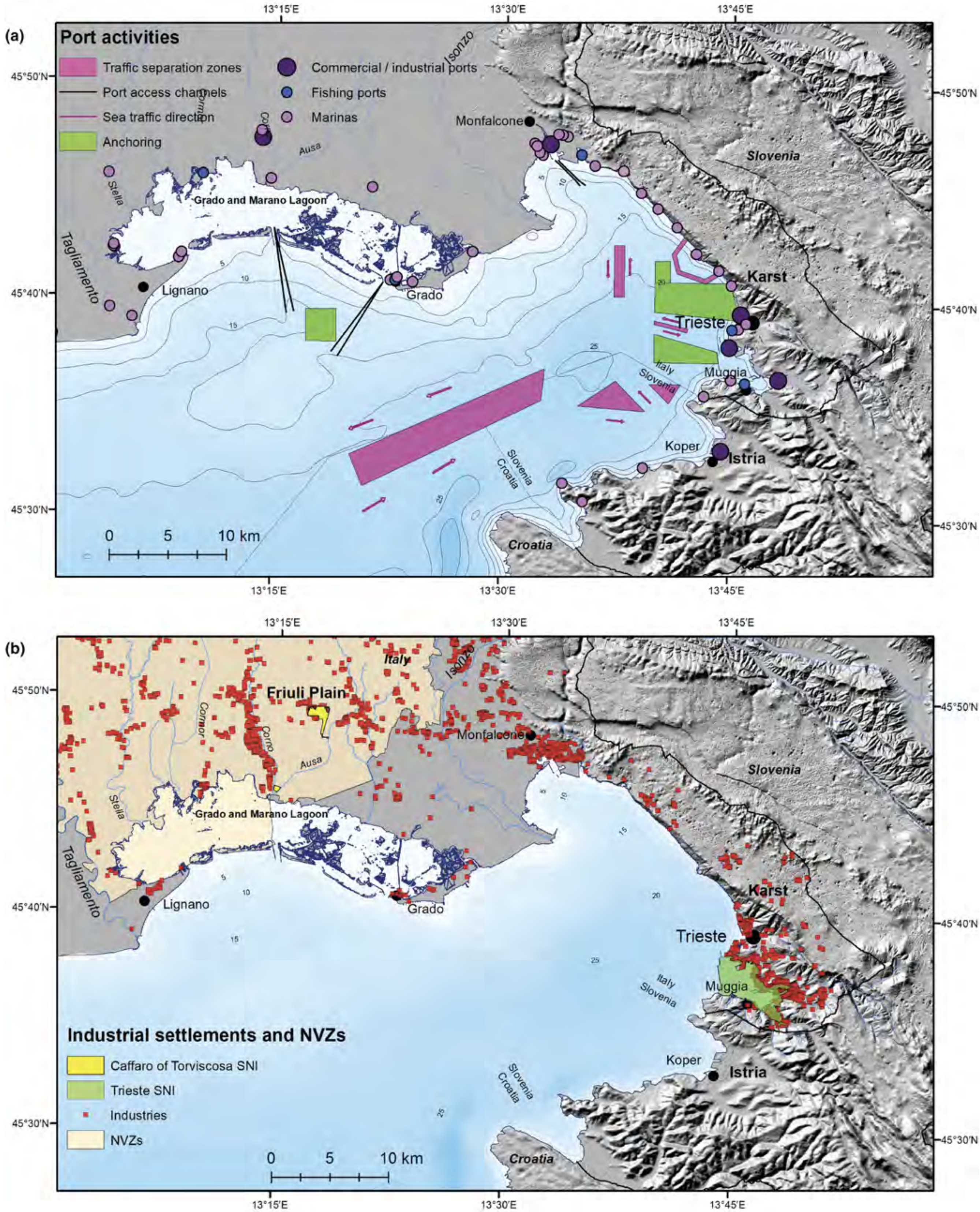

FIGURE 3 Anthropic activities carried on in the Gulf of Trieste (a) and in the surrounding onshore area (b). In (a) are indicated the port activities: the commercial/industrial ports of Trieste, Koper, Monfalcone, Porto Nogaro and the Fishing ports of Grado, Marano Lagunare, Monfalcone, Muggia, Trieste, Villaggio del Pescatore (from ADRIPLAN, 2017), Traffic separation zones, port access channels, sea traffic direction and anchoring area (from the Official State Nautical Chart, from Punta Tagliamento to Pula n. 39, scale 1: 100,000, published by the Hydrographic Institute of the Italian Navy, 2016). In (b) are indicated the Industrial settlements (from openstreetmap), the Caffaro of Torviscosa Site of National Interest (SNI) and Trieste SNI (from MATTM, 2017) and nitrate vulnerable zones (NVZs) (from IRDAT FVG, 2017).

TABLE 1 Characteristics of the main port centres.

Port centers	
Port of Trieste	Port areas: 2.3 million m^2, along 20 km of coastline Storage areas: 925,000 m^2 of which approximately 500,000 m^2 are covered Docks length: 12 km Operational berths: 58 (for conventional, multifunctional ships, container ships, Ro-Ro/ferries, oil tankers, chemical tankers, passengers, etc.) Maximum depths: 18 m Railway track length: 70 km 2 entry/exit channels: North Channel and South Channel 4 breakwaters Total goods handled in 2019: 61,997,445 tons Container number: 789,594 TEU Rail traffic: 9,771 trains
Port of Monfalcone	Area development: 140,000 m^2 Docks length: 1.5 km Sea depth: 9.5 – 11.7 m Access channel to the port: 4.5 km long, 166 m wide Total goods handled in 2019: 4,093,425 tons

of nutrient pollution, with maximum concentrations near the river mouths of the and with greater impacts in the Marano lagoon than in the Grado lagoon, due to the lower influence of the rivers flowing there (IRDAT FVG, 2017).

2.2.4 | Fishing pressure

In the study area, fishing pressure is about one fifth of the total pressure of the northern Adriatic coast and more than 60% of it is related to shellfish farming, which is particularly developed in the Grado and Marano Lagoon and along the eastern coast of the gulf (ARPA FVG, 2014b) (Figure 4a).

2.2.5 | Anthropogenic elements on the seabed

Several anthropogenic elements have been identified on the seabed of the Gulf of Trieste, that have significantly altered the natural environment.

Seabed features include port access channels, underwater pipelines, authorised areas for the discharge of dredging sediment, other anthropogenic reliefs on the seabed produced by discharges not associated with authorised sites, and dredged channels (Figure 4b).

In particular, in the Muggia Bay, an artificial channel has been dredged on the seabed, extending over a length of about 4700 m, and varying in width from 110 m, at the north-western part to 1100 m, at south-eastern part. The channel was dredged for the navigation of oil tankers that dock at the Trieste—Ingolstadt oil pipeline terminal, built between 1965 and 1967 (Romano, 2008).

In the eastern part of the gulf, to the west of the dams, a large relief was identified, with a length of almost 5 km, a width of about 2.5 km, covering an area of about 9.25 km^2, with maximum thickness of about 6 m and an estimated volume of $11.8 \times 10^6 m^3$. This relief is also mapped in the current nautical and bathymetric charts. The relief is of anthropogenic origin and is supposed to have resulted from the discharge of sediments resulting from the dredging of the channel for the oil tankers (Pagano, 2018).

3 | METHODS

The approach used to assess anthropogenic pressure in the Gulf of Trieste has been accomplished by integrating the MCDA within a GIS, leveraging the advantages of both tools. The GIS integration allowed for the organisation, management and integration of the geographical data required for the study and the MCDA facilitated the configuration of the decision problem by modelling the preferences of the decision-makers (Malczewski, 1999). The final output of the process, described in detail in the following paragraphs, consists of specific thematic maps that provide a clear and visual representation summarising the factors and criteria involved, thus helping decision-makers to better understand the spatial patterns of anthropogenic pressure in the Gulf of Trieste.

3.1 | Indicators used

The assessment starts from the geographical data available for the coastal study area that includes the Gulf of Trieste, spanning from the north-west corner of the Istria Peninsula to the mouth of the Tagliamento River and extending 500 m inland from the coastline. According to panel of local experts and decision makers, a series of maps (indicators) were produced representing different factors or criteria relevant to the assessment of anthropogenic pressure and the quality of the natural environment. For each criterion, values were assigned on a continuous scale of magnitude, ranging from "good" (100) to "bad" (0). Within each specific indicator, higher values represent favourable conditions or a lower level of criticality, while lower values indicate unfavourable conditions or a higher level

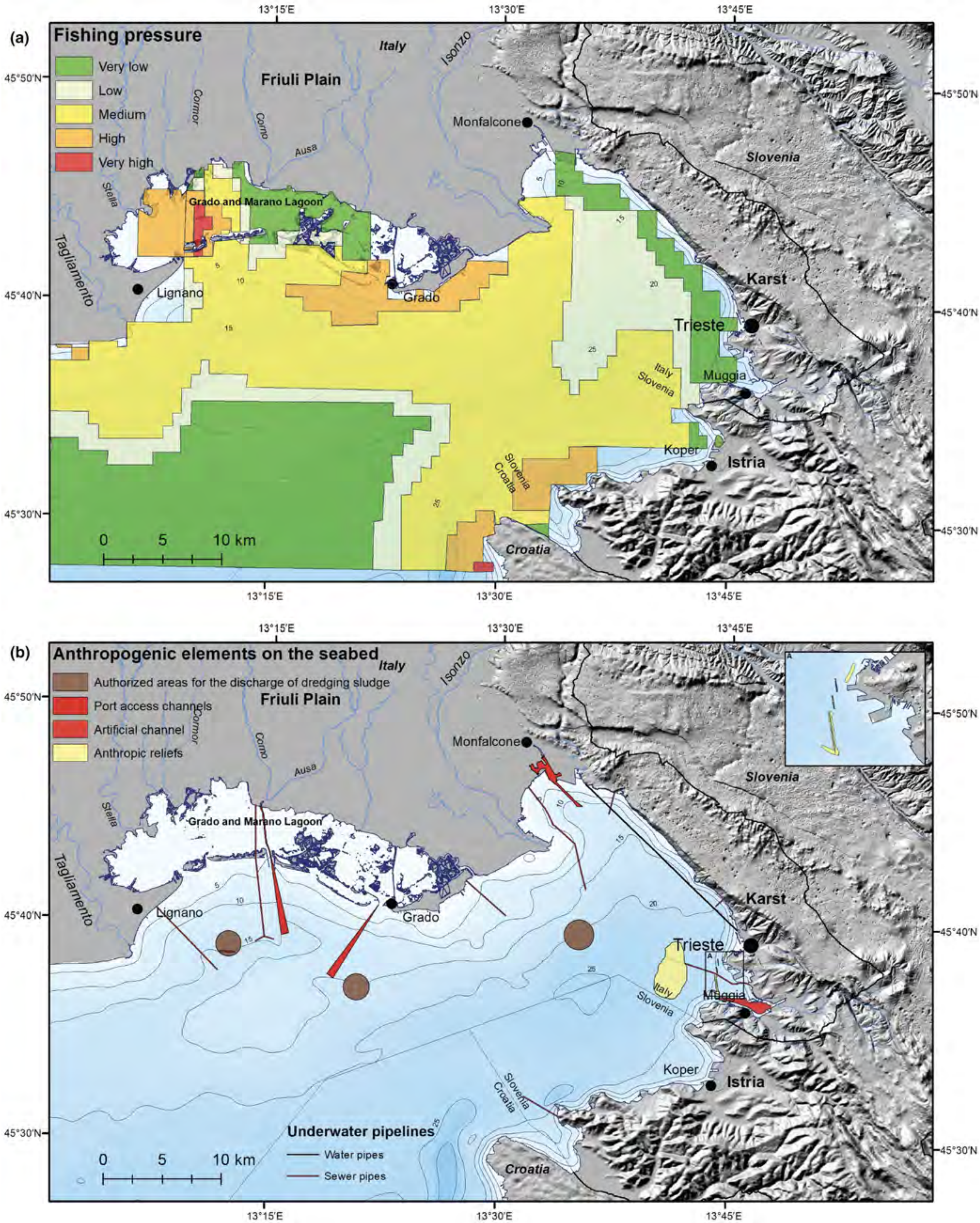

FIGURE 4 Anthropic activities. (a) Represents the fishing pressure (from ADRIPLAN, 2017); (b) represents the anthropogenic elements on the seabed (Pagano, 2018).

of criticality. The use of a continuous scale allows for more nuanced assessments and facilitates differentiation between different degrees of quality or impact. Some indicators were categorised into predefined classes, and scores were assigned accordingly. The normalisation process is implicit in this case, as the values are directly assigned to the classes on a scale from 0 to 100. For continuous indicators like density, a linear normalisation approach was applied based on the minimum and maximum values in the study area. Linear normalisation, inverse or direct, is a straightforward and commonly used technique to transform data into a consistent and comparable scale. Table 2 details the operations performed for each indicator, including the processing steps applied to the available data (assignment, intensity, density, distance) for the assignment of scores based on the types found and/or spatial relationships. Some maps are then presented (Figures 5 and 6).

3.2 | Weight assignment

Based on the experts' judgement, to each criterion is assigned a relative weight (this also ranging from 0 to 100) corresponding to its relative importance (between) in defining the state of the environment. This importance is averaged between experts and entered into a table for each criterion.

The resulting weight that each indicator has in the creation of the final map is given by the average importance of the indicator divided by the total of the importance values assigned to all indicators (Table 3). Removing or adding indicators does not change the assigned importance, but the weighting must be recalculated for the remaining subset of indicators. For instance, to create a naturalness map relating to the seabed, only those indicators that can influence the state of the seabed were selected (Table 4).

All assigned weights must sum to 100, so that the weighted sum of the values of all indicators multiplied by their percentage in the final map can give a maximum value of 100.

3.2.1 | Weighted sum of the indicators

The indicators used in the assessment are derived from data sources of different origins and formats. To facilitate their integration, the indicators are reprocessed into aligned and overlapping raster maps, grids with a cell size of 50 m. This spatial data format allows for consistent spatial analysis and facilitates the use of Weighted Sum tools. The Weighted Sum tools, overlying cell values, combine and weight the multiple raster inputs (the set of indicators) producing comprehensive integrated assessment maps such as vulnerability maps or naturalness maps (Figure 7).

To provide an example, if the ecological status indicator has a value of 100 in a given cell, its maximum contribution to that location would be 4.4 (100 multiplied by 4.4 and divided by 100). The final value of this cell in the integrated analysis map would be 100 only if all the other indicators also score the same maximum value.

4 | RESULTS

Two vulnerability maps have been evaluated: the vulnerability map of the seabed (Figure 8a) and the vulnerability map of the marine environment as a whole (Figure 9a).

The most suitable areas represented in the map will be those broadly combining at the same time the highest level of environmental quality and protection and the lowest anthropogenic impacts or pressures.

The map of the vulnerability of the seabed was created by a weighted combination of only those indicators that may affect the state of the seabed:

- Fish farms, due to fishing carried out with dredgers and turbo blowers which can have a negative impact on both the seabed and ecosystems, as they remove and destroy everything they encounter along the way, leaving clear traces on the seabed.
- Outcrops, as an area of environmental value.
- Anchorage area, being a threat to both mechanical impacts on the seabed and for the ecosystems.
- Anthropogenic elements on the seabed that cause alteration of the natural morphology of the seabed (port access channels, underwater pipelines, authorised areas for the dredged sediment discharge, other anthropogenic reliefs on the seabed resulting by sediment discharges not related to the authorised sites, and dredged channels).
- Natura 2000 sites, Ramsar sites and Nature Reserves, as they are protected areas where anthropogenic impacts on the seabed should be zero.

The vulnerability map of the marine environment as a whole was produced by a weighted combination of all indicators.

After the weighted combination, both maps were statistically reprocessed to obtain a smoother representation. In this process, each cell was assigned the average of the values of all cells within a radius of 1 km (Figures 8b and 9b).

The analysis highlighted areas with different degrees of environmental vulnerability due to anthropisation, and identified the most critical areas in the Gulf of Trieste.

Both maps show that large areas of the seabed and marine environment are affected by anthropogenic pressures, while those with minimal or non-existent impacts are very limited.

4.1 | Vulnerability map of the seabed

The vulnerability map of the seabed shows that the highest values, in the range 67–87, are found only in the westernmost part of the Grado and Marano Lagoon and in the north-eastern part of the gulf, as this is where most of the natural areas with a high level of protection and conservation overlap (Natura 2000 sites, Ramsar sites, Regional Natural Reserves). In the remaining part of the lagoon the values are in the middle range 48–56, due to the presence of

TABLE 2 The indicator maps created.

	Indicator	Score assignment
Environmental data	Natura 2000 sites (SIC and SPAs) Ramsar sites Natural reserves	100: inside areas 0: outside areas
	Outcrops (trezze and geosites) Site location with a buffer zone of 150m radius. In case of overlap, the geosite prevails	100: geosites 80: trezze
	TraC waters ecological status classification	100: good status 70: sufficient status 40: poor status 100: external areas, in continuity with the areas of "good condition" and further away from the coastal area
	TraC waters chemical state For areas with no data, no results are presented in case of overlapping of more maps. This workaround—the intermediate value—allows to account for important data layers where available.	100: good status 0: non-good status 50: outside areas, where there is no data available, since they are not affected by the analyzes for the determination of the chemical status
	Classification of mollusc farming	100: A zone—low level of contamination and outside areas 60: B zone—presence of contamination 0: C zone—high level of contamination
	Fish farms	100: outside areas 0: fish farms
	Anchoring	100: outside areas 0: inside areas
Anthropic data	Sea traffic (from MarineTraffic, marinetraffic.com, 2018)	100: outside areas 60: moderate traffic 0: heaviest traffic
	Fishing pressure (by boats <12m)	100: areas without fishing pressure 0–100: based on the type of pressure exerted
	Anthropogenic elements on the seabed	100: outside areas 0: anthropogenic elements
	SNI	100: outside areas 0: Trieste and Torviscosa SNI
	Industrial density Urbanisation density Port density	Proxy indicators for anthropisation (by industrial activity, by urbanisation and by port), built starting from the location of industries, buildings and ports. Value is based on the density of their presence in a radius of 10km along the coast. A higher weight (10 times), was assigned to commercial ports with respect to tourist ports due to major traffic and activities
	Drains	The intensity of wastewater discharges was evaluated according to the minimum distance from the coast of the emitting point. At design level, the discharge location and distance from the coast is calculated according to the predicted emission intensity. Starting from the emission point, the intensity decays until it reaches 0 at the minimum distance that the point has from the nearest coast. If the intensities of the emission points overlap, the values are added up. For the pipeline located in the lagoon of Grado and Marano, only one emission point was considered

natural areas. The areas with the lowest values, in the range 11–31, are located in the northern part of the gulf, immediately south of the coast from Grado to Lignano, and in the offshore close to Trieste, where most of the human activities are carried out (shellfishing with dredges and turbo blowers, anchoring boats) or the presence of anthropogenic elements on the seabed can damage the natural environment and even permanently alter the natural morphology. In the remaining part of the gulf, the values are generally not high and are in the range 32–40, due to the lack of any kind of protection of the areas (Figure 8a,b).

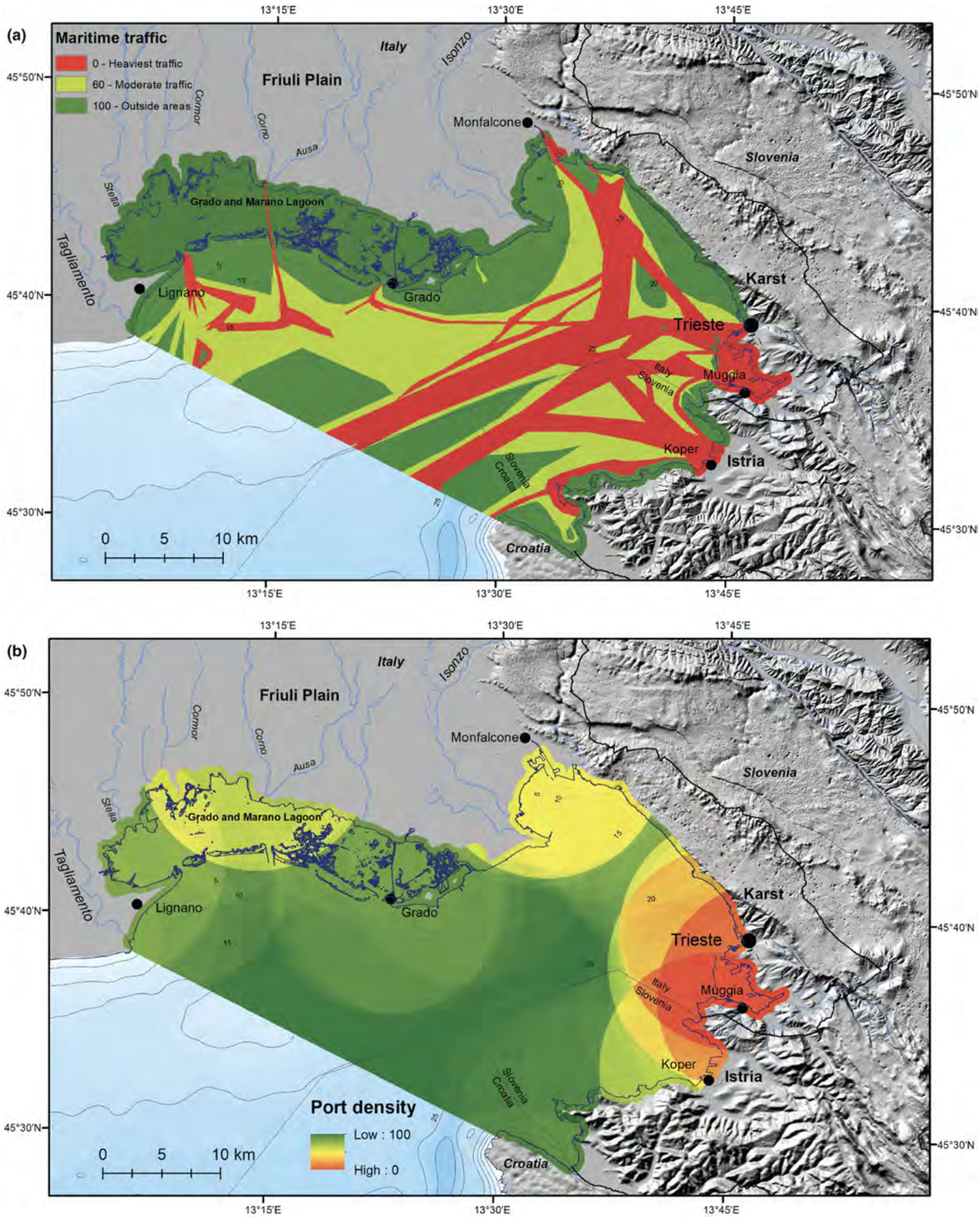

FIGURE 5 The map with the computed indicators. (a) Represents the Maritime traffic indicator; (b) represents the Port density indicator.

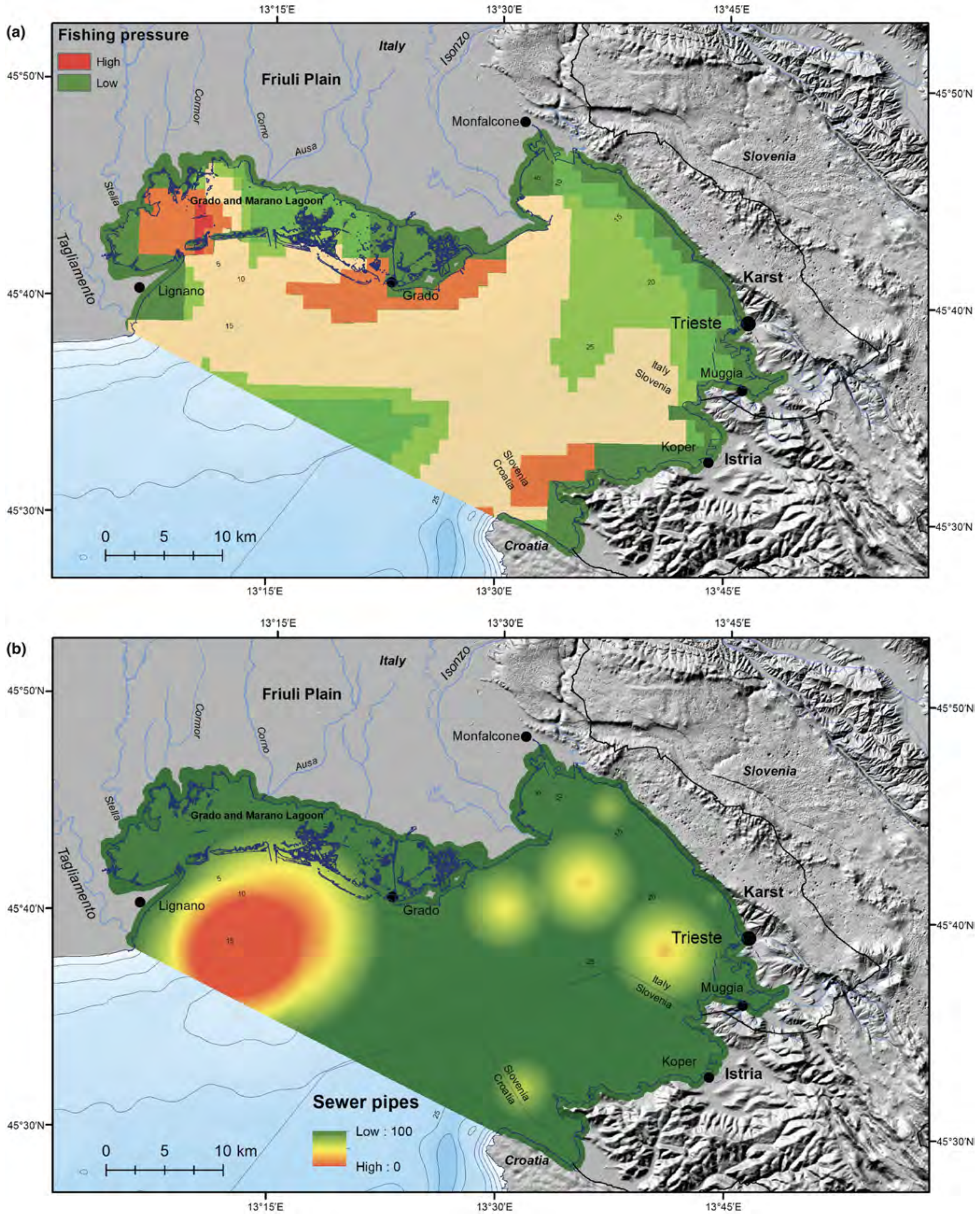

FIGURE 6 The map of the computed indicators. (a) With the indicator for fishing pressure, and (b) with the sewer pipes indicator.

TABLE 3 Assignment of weights for all indicators considered.

Indicator	Average importance	Weight
Aquaculture	80	5.8
Outcrops	100	7.3
Anchorage	70	5.1
Industrial areas	70	5.1
Buildings	50	3.6
Seabed morphology	80	5.8
Natura2000	90	6.6
Ports	70	5.1
Fishing pressure	70	5.1
Fishing quality	60	4.4
Ramsar sites	90	6.6
Reserves	100	7.3
Drains	80	5.8
SNI	80	5.8
Chemical status	60	4.4
Ecological status	60	4.4
Traffic	80	5.8
NVZ	80	5.8

Abbreviations: NVZ, nitrate vulnerable zones; SNI, Sites of National Interest.

TABLE 4 Assignment of weights for seabed indicators.

Indicator	Average importance	Weight
Aquaculture	80	13.1
Outcrops	100	16.4
Anchorage	70	11.5
Seabed morphology	80	13.1
Natura2000	90	14.8
Ramsar sites	90	14.8
Reserves	100	16.4

4.2 | Vulnerability map of the marine environment

In the vulnerability map of the marine environment, the highest values, in the range 68–85, are found in a limited area in the westernmost part of the Marano and Grado Lagoon, in the eastern part of the Marano and Grado Lagoon, at the mouth of the Isonzo river, and on the north-eastern coast, in particular due to the overlapping of protected natural areas. The lower values, in the range 41–57, are found in the facing areas of Trieste and Muggia, where activities with high anthropogenic pressure overlap, such as the port, urbanisation, industrial activities and maritime traffic which generally affects the central part of the gulf. Relatively low intermediate values, in the range 58–64, are detectable in the central part of the gulf, mainly due to fishing pressure affecting the whole study area.

In the Marano and Grado Lagoons, the values are different, because in this area the contribution of the "Ecological status of TraC waters", of the "Chemical status of TraC waters" and of the "ZVN of agricultural origin" must be taken into account.

In particular, the western part of the lagoon is affected by the presence of nitrates, so that the values are lower overall.

Furthermore, the lagoon of Marano and the lagoon of Grado are subjected to different pressures related to the inputs of the various rivers and the types of anthropic activities existing in the areas of the lagoon drainage basin. Therefore, the lagoon environment presents different levels of pollution from nutrients, with maximum concentrations near the river mouths and with greater influences in the lagoon of Marano rather than in that of Grado, which has on average much lower nitrate concentrations than that of Marano, due to the lesser influence of the inflowing rivers.

Especially in the western part of the lagoon, the presence of nitrates potentially interferes, so that the values are lower overall (Figure 9a,b).

5 | DISCUSSION

Based on a series of collected environmental data and other data from databases available from institutions or different authorities, it was therefore possible to create maps highlighting the areas of greatest naturalness and the areas of greatest vulnerability, which can be used to check where interventions are needed to restore environmental balances that could threaten the sustainable development of the area in the near future.

While Halpern et al. (2008) and Andersen et al. (2013) calculated the Cumulative Impact Assessment for the MSP for the Adriatic and Ionian Region using a 1×1 km grid, and Manea et al. (2019) attempt to quantify and map the supporting ES of the Adriatic Sea, the purpose of this analysis is to evaluate the anthropic pressures in a much more limited area, the Gulf of Trieste, but at a high-resolution scale with a 50×50 m grid. The resulting high-resolution vulnerability maps highlight areas with different degrees of environmental fragility due to anthropisation at a high level of detail, and make evident elements that have limited spatial distribution such as, for example the protected natural areas and the area of high fishing pressure in the Grado and Marano Lagoon. The greatest anthropogenic pressure comes from the main industrial and port activities, while the seabed vulnerability map shows that the anchoring, the discharge of dredging sludge and the fishing of molluscs with dredgers and turbo blowers are the greatest threats to the seabed, as they alter the natural morphology and have a negative impact on ecosystems. The anthropogenic relief of about 10 km^2 and about 12 million m^3 located on the seabed north-west of Muggia is an example of how human activities can completely alter the natural seabed and ecosystem.

The maps show that the most natural areas are due to the overlap of areas with high levels of protection and conservation, demonstrating that these measures are crucial for healthy seas. Marine protected areas play a key role in protecting marine ecosystems and increasing their resilience. It is therefore necessary that their

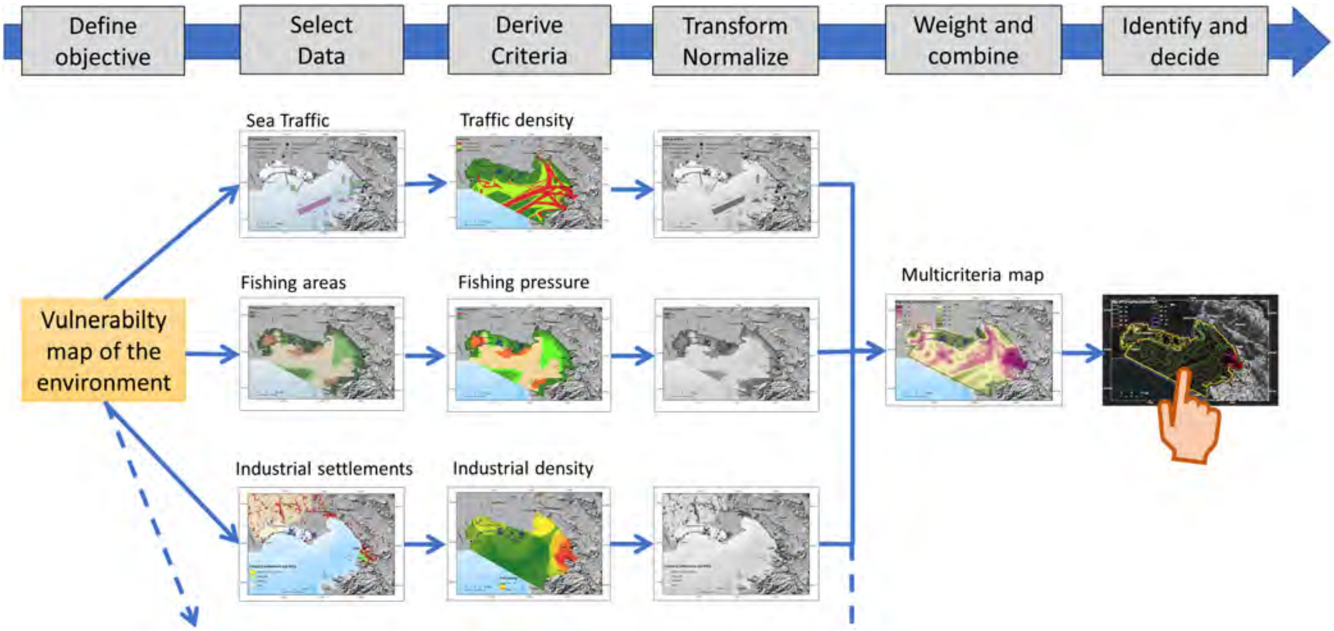

FIGURE 7 Modelling workflow for vulnerability maps.

number increases, that they remain in good health and interconnected through ecological corridors.

Indeed, the fourteenth of the UN's Sustainable Development Goals aimed to preserve at least 10% of coastal and marine areas by 2020. While this goal has not yet been achieved (only 3.5% of the world's oceans are currently protected), it is expected that the proportion of protected oceans and seas will increase to 30% by 2030.

Although 9.68% of the Mediterranean Sea is protected, only 2.48% of the marine areas are protected in various ways (according to international and national standards) and have their own management plans. Those that implement their own plans ensuring management effective are even fewer, the 1.27% and they are located on the northern coast of the Mediterranean. The percentage of the Mediterranean Sea under maximum integral protection is only 0.03%. As for Italy, it is apparently in a good situation as it protects 19.12% of its territorial waters (0–12 nautical miles) for various reasons and has management plans for 18.04% that theoretically protect our seas, in reality the management is only implemented in 1.67% of Italian marine waters (Greenreport, 2019).

The MCDA integrated with a GIS has been applied in coastal management, for example by Barzhekar et al. (2021) that point out that this method extends the long-term applicability of tools employed by coastal managers. One of the advantages of multicriteria analysis is in the possibility to collect and evaluate the elements that contribute to the decision using the most appropriate evaluation method but one of the main limitations of this type of analysis is precisely its subjectivity. The criteria used for decision-making are based on available data and expert opinion. The relative importance of these criteria can be determined by various methods, such as averaging expert judgements. Even if this approach helps to reduce subjectivity to some extent, it does not guarantee complete accuracy in determining the weights for the final combination of indicators. It is important for decision-makers to be aware of the potential limitations of multicriteria vulnerability maps taking in consideration the biases in the criteria selection and in the weight determination process.

The use of GIS makes it possible to integrate the analysis carried out with additional data, in order to follow the evolution of environmental legislation, to study a specific area or phenomena. For example, it would be very interesting to filter Automatic Identification System boat tracks based on the size of the boats and the sailing speed parameter, in order to identify the number of boats with higher speed, that have a greater impact on the coastline due to the waves generated. Instead, boats with speeds close to zero can be considered stationary and therefore probably anchored and impacting the seabed.

Updating vulnerability maps, or creating them newly, would make it possible to verify any improvements or degradation in the areas considered and consequently, the appropriateness of the interventions carried out.

MSP is a crucial tool for implementing the blue economy and guiding development and investment in maritime activities, promoting the sustainable development of the marine and coastal environment and ensuring the protection of marine resources by applying an ecosystem approach, considering the intensification of cross-border cooperation and land-sea interactions. The vulnerability maps are a useful analytical tool to identify the most critical areas where possible actions can be planned to maintain a healthy and sustainable productive marine environment. Distinguishing between the areas of greatest environmental fragility from the most secure and long standing ones is a fundamental step to manage and solve the conflicts between economic development and environmental health, preventing the destabilisation of marine ES and at the same time fully developing the potential of the blue growth in compliance with the United Nations Sustainable Development Goals.

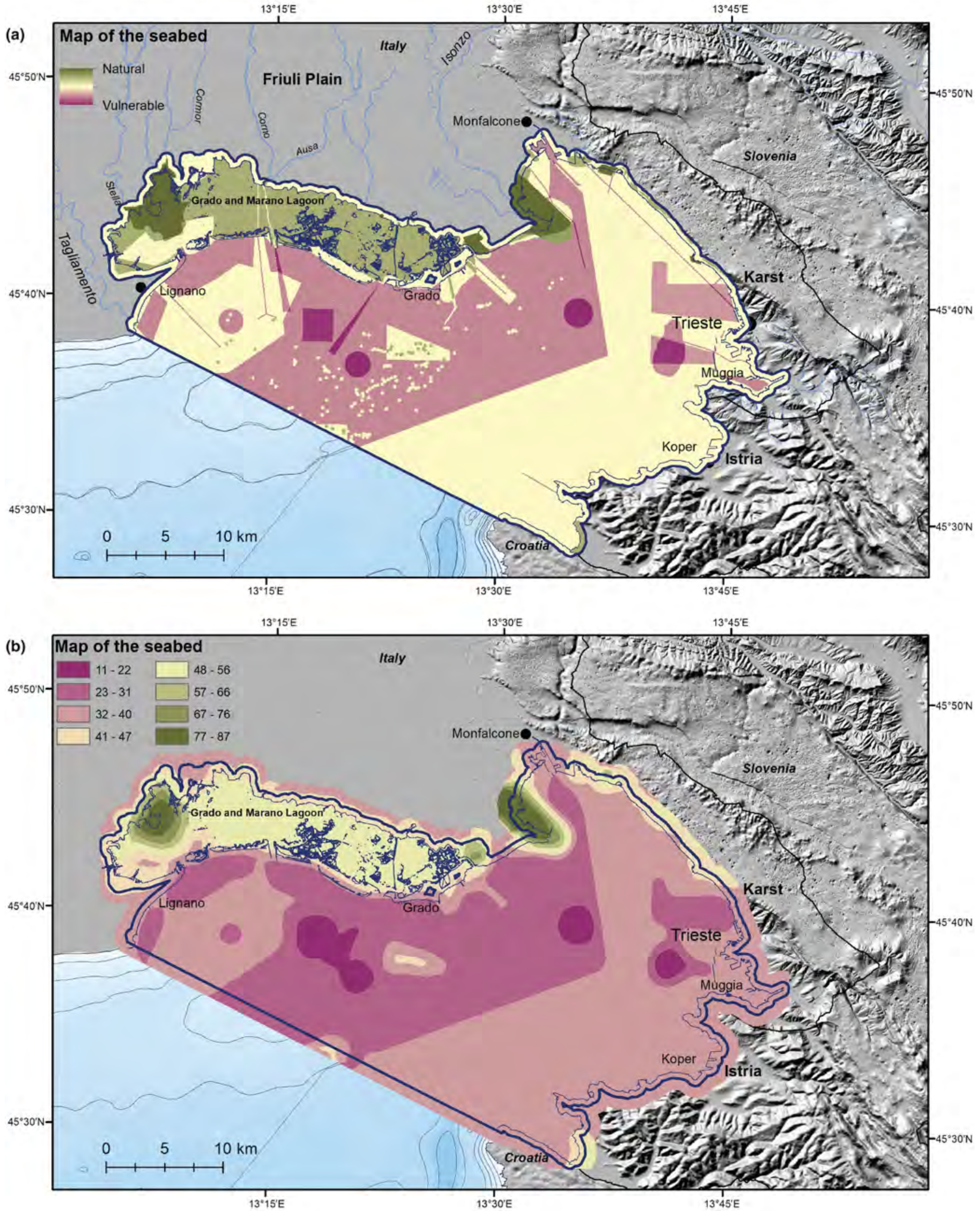

FIGURE 8 Vulnerability map of the seabed, with the purple colour indicating the greater anthropisation and the green colour indicating the greater naturalness. (a) Represents the used indicators, while (b) represents the vulnerability map of the seabed, made from the statistical reprocessing of the (a) map, assigning to each cell the average of the values of all the cells present in the radius of 1 km.

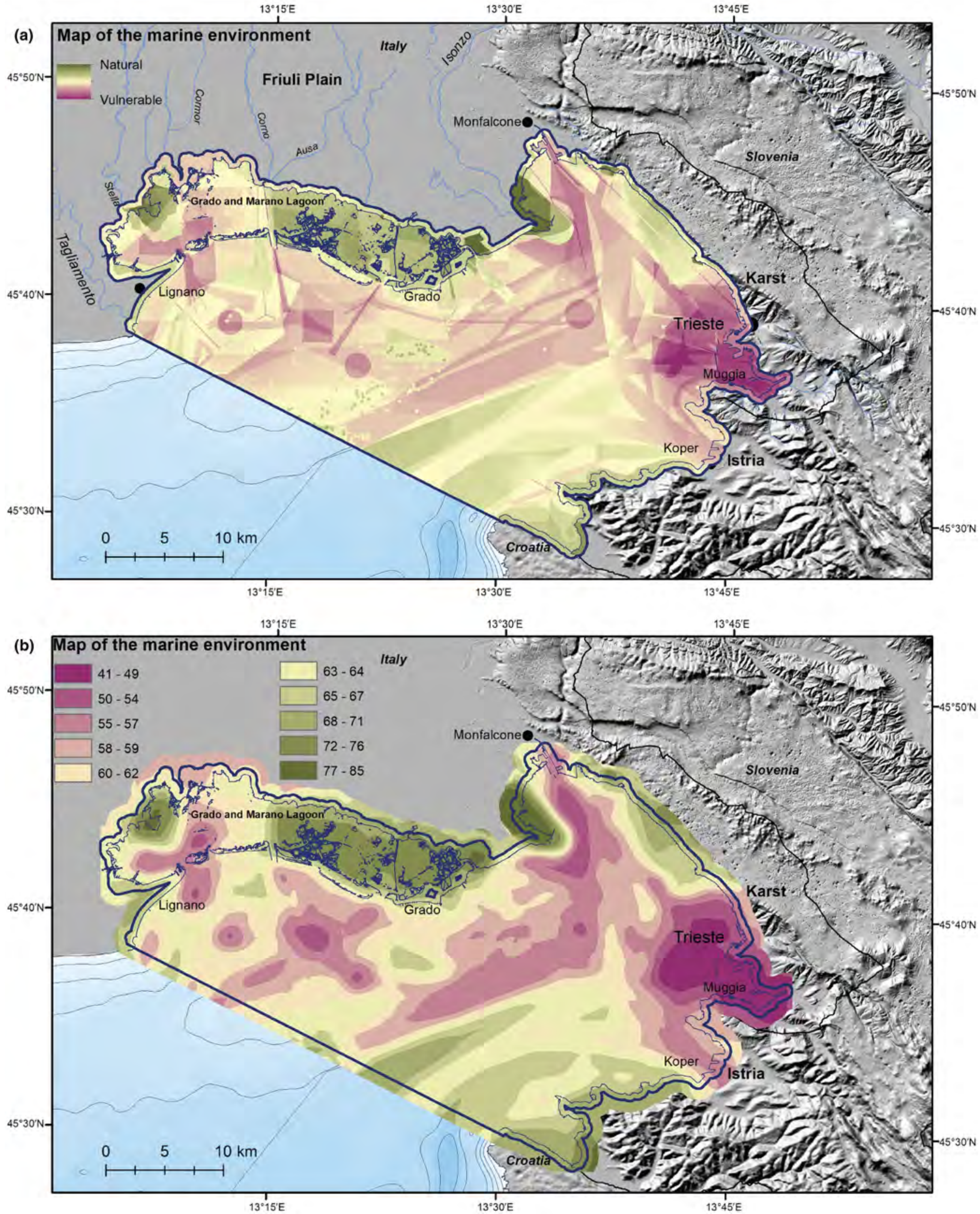

FIGURE 9 Vulnerability map of the marine environment with the purple colour indicating greater anthropisation, and the green colour indicating the greater naturalness. (a) Represents the used indicators, and the (b) represents the vulnerability map of the marine environment, created by statistical reprocessing of the (a) map, reassigning to each cell the average of the values of all the cells present within a radius of 1 km.

6 | CONCLUSIONS

Human pressures on the seas and oceans threaten their health and their enormous socio-economic potential and certainly cause environmental but also economic and social damage. The vulnerability maps highlighted areas with different degrees of environmental fragility due to anthropisation. In general, the most stressed areas are concentrated in correspondence with the main industrial and port activities, while the most natural areas are due to the overlapping of areas with a high level of protection and conservation. In addition, the anthropogenic activities have altered the natural morphology of the seabed and could have negative impacts on ecosystems and biocenoses, as in the case of the relief of about 10 km^2 and about 12 million m^3 located on the seabed north-west of Muggia, whose morphology is not compatible with natural geological processes and is therefore certainly of anthropogenic nature.

The distinction between the areas of higher environmental fragility from the less anthropised area is a fundamental step for the sustainable management of marine and coastal areas in order to promote responsible blue growth, limit conflicts between economic development and environmental health, and not compromise the ES of the marine environment.

Blue growth is based on the balance between man and the environment, promoting human activities that use the sea, coasts and seabed as resources for industrial activities and the development of services, inserted in a perspective of sustainability.

Sustainable development is the basis of the blue economy, a long-term strategy of the European Union, which the directives on the Marine Environment Strategy (2008/56/EC) and MSP (2014/89/EU) were adopted to promote.

The vulnerability maps produced are a valid analytical tool to assess where interventions are needed to restore environmental balances that could threaten the sustainable development of the area in the near future. In doing so, the most environmentally critical areas are identified in order to plan possible intervention actions with the aim of a having healthy and productive marine environment and fully developing the potential of blue growth.

AUTHOR CONTRIBUTIONS

Mariangela Pagano, Michele Fernetti and Martina Busetti conceived the idea and designed methodology. Mariangela Pagano conducted the collection. Mariangela Pagano and Michele Fernetti analysed the data. Mariangela Pagano and Martina Busetti led the writing of the manuscript. Michele Fernetti contributed for the technical section and Mounir Ghribi and Angelo Camerlenghi contribute for marine policy perspective. All authors contributed critically, reviewed and edited the draft and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used in this work are publicly available.

ORCID

Martina Busetti https://orcid.org/0000-0001-7039-3282
Mounir Ghribi https://orcid.org/0000-0003-2233-2420
Angelo Camerlenghi https://orcid.org/0000-0002-8128-9533

REFERENCES

ADRIPLAN. (2017). http://adriplan.eu/

Andersen, J. H., Stock, A., Mannerla, M., Heinänen, S., & Vinther, M. (2013). *Human uses, pressures and impacts in the eastern North Sea*. Aarhus University, DCE—Danish Centre for Environment and Energy. (136 pp.) Technical Report from DCE—Danish Centre for Environment and Energy No. 18. https://www2.dmu.dk/Pub/TR18.pdf

ARPA FVG. (2013a). *La biodiversità in FVG*. http://cmsarpa.regione.fvg.it/cms/istituzionale/servizi/biodiversita/per_saperne_di_piu/La-biodiversit-in-Friuli-Venezia-Giulia.html

ARPA FVG. (2013b). *Rete Natura 2000*. http://cmsarpa.regione.fvg.it/cms/istituzionale/servizi/biodiversita/Approfondimenti/Rete-Natura-2000.html

ARPA FVG. (2013c). *Zone umide*. http://cmsarpa.regione.fvg.it/cms/istituzionale/servizi/biodiversita/Approfondimenti/Zone-umide.html

ARPA FVG. (2014a). *Le acque marino-costiere e lagunari*. https://arpa.fvg.it/cms/tema/acqua/acquemarino-costiere-e-lagunari/approfondimenti/Acque-marino-costiere-e-lagunari.html

ARPA FVG. (2014b). *Stato degli ambienti marini e costieri*. https://arpa.fvg.it/cms/tema/acqua/acquemarino-costiere-e-lagunari/approfondimenti/Acque-marino-costiere-e-lagunari.html

ARPA FVG. (2015). *Siti inquinati*. http://cmsarpa.regione.fvg.it/cms/tema/suolo/approfondimenti/Siti-contaminati.html

ARPA FVG. (2017). *Molluschicoltura: l'ambiente per la tutela della salute*. Prevenzione sanitaria molluschi e acque marine e di transizione del FVG. http://cmsarpa.regione.fvg.it/cms/tema/acqua/acque-marino-costiere-e-lagunari/approfondimenti/schede/Molluschicoltura-l-ambiente-per-la-tutela-della-salute.html

ARPA FVG. (2020). *Piano regionale di tutela delle acque*. http://cmsarpa.regione.fvg.it/cms/tema/acqua/acque-marino-costiere-e-lagunari/piani/Piano-Regionale-di-Tutela-delle-Acque.html

Arso. (2017). *Ministry of the environment and spatial planning*. Slovenian Environment Agency . https://gis.arso.gov.si

Barbanti, A., Campostrini, P., Musco, F., Sarretta, A., & Gissi, E. (2015). *Conclusioni e raccomandazioni del progetto ADRIPLAN. Un manuale breve per la pianificazione dello spazio marittimo nella regione Adriatico-Ionica* (77 pp.). CNR-ISMAR.

Barzehkar, M., Parnell, K. E., Soomere, T., Dragovich, D., & Engström, J. (2021). Decision support tools, systems and indices for sustainable coastal planning and management: A review. *Ocean & Coastal Management*, *212*, 105813. doi:10.1016/j.ocecoaman.2021.105813

Brambati, A., & Catani, G. (1988). Le coste e i fondali del Golfo di Trieste dall'Isonzo a Punta Sottile: aspetti geologici, geomorfologici, sedimentologici e geotecnici. *Hydrores Information*, *5*(6), 13–28.

Distretto Idrografico Delle Alpi Orientali. (2014). Progetto di aggiornamento del Piano di gestione del Distretto Idrografico delle Alpi Orientali—Secondo ciclo di pianificazione (2015–2021). *Stato elle Acque Superficiali e Sotterranee*, *5*, 57.

EMODnet Digital Bathymetry. (2018). *EMODnet bathymetry consortium*. Retrieved September 14, 2018, from https://www.emodnet.eu

EU-DEM. (2017). *Copernicus land monitoring service*. https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem

Furlan, E., Slanzi, D., Torresan, S., Critto, A., & Marcomini, A. (2020). Multi-scenario analysis in the Adriatic Sea: A GIS-based Bayesian network to support maritime spatial planning. *Science of the Total Environment*, *703*, 134972. https://doi.org/10.1016/j.scitotenv.2019.134972

García-Ayllón, S. (2018). GIS assessment of mass tourism anthropization in sensitive coastal environments: Application to a case study in the Mar Menor Area. *Sustainability*, *10*(5), 1344. doi:10.3390/su10051344

García-Ayllón, S. (2019). New strategies to improve co-management in enclosed coastal seas and wetlands subjected to complex environments: Socio-economic analysis applied to an international recovery success case study after an environmental crisis. *Sustainability*, *11*(4), 1039. doi:10.3390/su11041039

Gissi, E., Menegon, S., Sarretta, A., Appiotti, F., Maragno, D., Vianello, A., Depellegrin, D., Venier, C., & Barbanti, A. (2017). Addressing uncertainty in modelling cumulative impacts within maritime spatial planning in the Adriatic and Ionian region. *PLoS One*, *12*(7), e0180501. doi:10.1371/journal.pone.0180501

Gordini, E., Falace, A., Kaleb, S., Donda, F., Marocco, R., & Tunis, G. (2012). Methane-related carbonate cementation of marine sediments and related macroalgal coralligenous assemblages in the Northern Adriatic Sea. In P. T. Harris & E. K. Baker (Eds.), *Seafloor geomorphology as benthic habitats* (pp. 183–198). Elsevier.

Greenreport. (2019). *Il Mediterraneo tra blue economy e aree marine protette di carta*. https://greenreport.it/news/aree-protette-e-biodiversita/il-mediterraneo-tra-blue-economy-e-aree-marine-protette-di-carta/

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., Lowndes, J. S., Rockwood, R. C., Selig, E. R., Selkoe, A., & Walbridge, S. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications*, *6*, 7615. https://doi.org/10.1038/ncomms8615

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., & D'Agrosa, C. (2008). A global map of human impact on marine ecosystems. *Science*, *319*(5865), 948–952. https://doi.org/10.1126/science.1149345

Hydrographic Institute of the Italian Navy. (2016). *Nautical chart from Punta Tagliamento to Pula, n. 39, 1:100.000*.

IRDAT FVG. (2017). *Infrastruttura regionale di dati ambientali e territoriali per il friuli Venezia Giulia*. https://irdat.regione.fvg.it/WebGIS/

Iyalomhe, F., Rizzi, J., Torresan, S., Gallina, V., Critto, A., & Marcomini, A. (2013). Inventory of GIS-based decision support systems addressing climate change impacts on coastal waters and related inland watersheds. In B. H. Singh (Ed.), *Climate change—Realities, impacts over ice cap, sea level and risks* (pp. 251–272). IntechOpen. https://doi.org/10.5772/51999

Jones, K. R., Klein, C. J., Halpern, B. S., Venter, O., Grantham, H., Kuempel, C. D., Shumway, N., Friedlander, A. M., Possingham, H. P., & Watson, J. E. M. (2018). The location and protection status of Earth's diminishing marine wilderness. *Current Biology*, *28*, 2683. https://doi.org/10.1016/j.cub.2018.07.081

Malczewski, J. (1999). *GIS and multicriteria decision analysis* (392 pp.). John Wiley and Sons.

Malczewski, J., & Rinner, C. (2015). GIScience, spatial analysis, and decision support. In J. Malczewski & C. Rinner (Eds.), *Multicriteria decision analysis in geographic information science* (pp. 3–21). Springer. https://doi.org/10.1007/978-3-540-74757-4

Manea, E., Di Carlo, D., Depellegrin, D., Agardy, T., & Gissi, E. (2019). Multidimensional assessment of supporting ecosystem services for marine spatial planning of the Adriatic Sea. *Ecological Indicators*, *101*, 821–837. https://doi.org/10.1016/j.ecolind.2018.12.017

MATTM. (2017). *Ministero dell'ambiente e della tutela del territorio e del mare*. https://www.governo.it/it/ministeri/ministero-dellambiente-e-della-tutela-del-territorio-e-del-mare

Mullick, M. R. A., Tanim, A. H., & Samiul Islam, S. M. (2019). Coastal vulnerability analysis of Bangladesh coast using fuzzy logic based geospatial techniques. *Ocean & Coastal Management*, *174*, 154–169. https://doi.org/10.1016/j.ocecoaman.2019.03.010

Pagano, M. (2018). *Analisi delle evidenze di attività antropiche nel fondo mare del golfo di Trieste in ambiente GIS, finalizzata ad una gestione sostenibile delle zone marine e costiere per favorire una crescita blu responsabile* (124 pp.). Master thesis at University of Trieste.

Piccinetti, C., Franzosini, C., Odorico, R., Piron, M., Zentilin, A., Franci, A., Grim, F., Kutin, S., Balducci, G. M., & Giannattasio, S. (2012). *Piano di gestione della pesca in mare Friuli Venezia Giulia*. Regione Autonoma Friuli Venezia Giulia(358 pp.). https://www.regione.fvg.it/rafvg/export/sites/default/RAFVG/economia-imprese/pesca-acquacoltura/FEP/FOGLIA16/allegati/Piano_di_gestione_delle_acque.pdf

Rangel-Buitrago, N., Neal, W. J., & De Jonge, V. N. (2020). Risk assessment as tool for coastal erosion management. *Ocean & Coastal Management*, *186*, 105099. https://doi.org/10.1016/j.ocecoaman.2020.105099

Regione FVG. (2017). *Aree naturali protette statali*. http://regione.fvg.it/rafvg/cms/RAFVG/ambienteterritorio/tutela-ambiente-gestione-risorse-naturali/FOGLIA402/

Regione FVG. (2021). *Le riserve naturali regionali*. http://regione.fvg.it/rafvg/cms/RAFVG/ambienteterritorio/tutela-ambiente-gestione-risorse-naturali/FOGLIA400/

Romano, R. (2008). Lavorare in funzione del porto. Principali tappe dello sviluppo del porto triestino fra Ottocento e Novecento. In T. Catalan & S. Zilli (Eds.), *O.T.I.S. Osservatorio del lavoro transfrontaliero per le aree portuali di Trieste, Monfalcone e Koper/Capodistria. UE Program INTERREG IIIA Italia-Slovenija 2000–2006* (pp. 67–87). La Mongolfiera Libri.

Trobec, A., Busetti, M., Zgur, F., Baradello, L., Babich, A., Cova, A., Gordini, E., Romeo, R., Tomini, I., Poglajen, S., Diviacco, P., & Vrabec, M. (2018). Thickness of marine Holocene sediment in the Gulf of Trieste (Northern Adriatic Sea). *Earth Science Data System*, *10*, 1077–1092. https://doi.org/10.5194/essd-10-1077-2018

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., & Watson, J. E. M. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications*, *7*, 12558. https://doi.org/10.1038/ncomms12558

Zacharias, M. A., & Gregr, E. J. (2005). Sensitivity and vulnerability in marine environments: An approach to identifying vulnerable marine areas. *Conservation Biology*, *19*, 86–97. https://doi.org/10.1111/j.1523-1739.2005.00148.x

Zampa, L. S. (2020). *New bathymetric maps of the north-east Adriatic Sea*. Technical Report 05/2020 OGS. National Institute of Oceanography and Applied Geophysics-OGS.

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