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A holistic DPSIR-based approach to the remediation of heavily contaminated coastal areas

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Abstract

This paper proposes a holistic approach to connect anthropogenic impacts to environmental remediation solutions. The eDPSIR (engineered-Drivers-Pressures-States-Impacts-Responses) framework aims at supporting the decision-maker in designing technological solutions for a contaminated coastal area, where the natural matrices need to be cleaned up. The eDPSIR is characterized by cause-effect relationships that are operationally implemented through three multidisciplinary toolboxes: (i) Toolbox 1, to connect driving forces with pressures, classifying the state of the system and allowing the identification of target contaminants and the extent of contamination; (ii) Toolbox 2, to

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quantify bioaccumulation also by identifying corresponding areas; (iii) Toolbox 3, to identify the most suitable remediation solutions for previously identified contaminated areas, named contamination scenarios. The eDPSIR was calibrated on the case study of the Mar Piccolo in Taranto (Southern Italy), one of the most complex and polluted areas in Europe. While the consolidated DPSIR allows for a strategic response by limiting the use of contaminated areas or reducing upstream pressures, the eDPSIR made it possible to structure with a semi-quantitative logic the problem of assisting the decision-makers in choosing the optimal technological remediation responses for each sediment scenario of contamination (heavy metal; organic compounds; mixed). Assisted natural attenuation was identified as the best remediation technology in terms of treatment effectiveness and smallest amount of impacts involved in the project actions. However, considering the scenario of mixed contamination, *in-situ* reactive capping reached a good rank with a value of the composite indicator equal to 99.5%; thermal desorption and stabilization/solidification recorded a value of 94.1% and 84.6%, respectively. The application of these toolboxes provides alternative means to interpret, manage, and solve different cases of global marine contaminated sites.

Capsule about main findings:

To develop and apply a new DPSIR-based decision-making approach capable of structuring and solving a complex problem such as heavily contaminated coastal areas.

Keywords: environmental health risk; marine sediments; multi-criteria analysis; pollution clean-up; sustainable remediation technologies

List of abbreviations

ANA = Assisted Natural Attenuation

BOD = Biochemical Oxygen Demand

CA = Cluster Analysis

COD = Chemical Oxygen Demand

CSM = Conceptual Site Model

DPSIR = Driving force–Pressure–Status–Impact–Response

EAC = Environmental Assessment Criteria

ERA = Ecological Risk Assessment

HQc = Hazard Quotient for chemistry

MCDA = Multi-Criteria Decision Analysis

MOA = Matrix of Alternatives

PAHs = Polycyclic Aromatic Hydrocarbons

PCA = Principal Component Analysis

PCBs = Polychlorinated Biphenyls

PCT = Paired Comparison Technique

PI = Preference Index

RTR = Ratio-to-Reference

SAW Simple Additive Weighing

SEA = Strategic Environmental Assessment

TOC = Total Organic Carbon

TWG = technical working group

WOE = Weight of Evidence

1. Introduction

The rapid economic development and industrialization have led to intensive urbanization with severe environmental problems. The main anthropic impacts, including wastewater discharge, industrial operations, and improper waste management, have compromised the whole ecosystems worldwide (World Health Organization, 2016). As a result, health problems have arisen for humans, due to the deterioration of environmental matrices and contamination of the trophic chains. The main pollutants contaminating natural ecosystems include microbial pathogens, organic compounds, metals/metalloids, emerging pollutants and modern pesticides (Bortone et al., 2020). Some pollutants would leave long-term damage to the ecosystem as in the case of Polychlorinated biphenyls (PCBs) (Li et al., 2009). Many approaches of environmental pollution management and mitigation measures related to ecosystem and human health are discussed in literature. Among them, the Driving force–Pressure–Status–Impact–Response (DPSIR) has been widely documented to analyze environmental issues. It is an approach that considers a chain of causal links starting with “driving forces” (e.g., economic and social needs), which create “pressures” (e.g., emissions, discharges) that in turn can change the state of environmental matrices, with consequent impacts on the environment and humans.

The existing literature on the models adopted to address pollution issues in coastal systems demonstrated a range of empirically oriented DPSIR applications. Atkins et al. (2011) integrated DPSIR with ecosystem services to create a framework to support decision-making in the marine environment. Cook et al. (2014) explored the interactions among coastal ecosystem pressures, states, and services, quantifying the impact through matrix-based analyses. Pastres and Solidoro (2012) showed dynamic models can help to improve understanding of ecosystem dynamics, thus providing a quantitative basis for the DPSIR framework. Zhang and Xue (2013) highlighted the need for further progress in the DPSIR logic, which could be achieved by establishing a unified information system and by improving indicator development for marine environmental problem assessment. By developing a system of indicators, Liu et al. (2018) highlighted how coastal ecosystems are dynamic and fixed-point monitoring should be conducted in the long-term to obtain dynamic data. Delgado et al. (2020) pointed out that in conflict situations the DPSIR model needs validation by local experts and social actors. Recently, Lewison et al. (2016) highlighted that the use of quantitative approaches in DPSIR research is relatively limited and partly due to the challenges of merging different data types. They concluded by showing how the search for cause-effect relationships as quantitative as possible is still a work in progress; new research should be directed towards the development of semi-quantitative relations between the various components of the DPSIR with a view to future generalization. Additionally, Bell (2012) explained why DPSIR, by its nature, is a narrowly formulated device, incompatible with most of multiple perspectives, which human interaction requires. Furthermore, it has been argued to be very limited when applied to sustainability research and to be incomplete as problem structuring and communication method (Wieket al., 2011).

The aim of this work is to propose an engineered version of the DPSIR framework able to assess which factors contributed to the pollution of a complex marine ecosystem and to identify the best technological responses in quantitative terms, such as the selection of appropriate remediation technologies. The new implemented framework, called eDPSIR, is based on three multidisciplinary steps, indicated with the term “toolboxes”, able to connect (i) driving forces with pressures and states, (ii) states with impacts, and (iii) technological responses with all the previous DPSIR components. One important purpose of this implemented DPSIR framework is to overcome the communication gap between scientific systems and public. The proposed approach was calibrated considering a complex and heavily contaminated site in Southern Italy, the Mar Piccolo of Taranto. To our knowledge, this is the first example of an attempt to explicitly integrate pressures, environmental issues, and potential remediation actions into a single framework.

2. Materials and methods

2.1. Case study

The Mar Piccolo of Taranto is a semi-enclosed marine basin in Apulia, Southern Italy (**Fig.**

1).

Fig. *1*. Localization of the Mar Piccolo case study.

It has a surface area of 21 km^2 divided in two inlets, called First Seno and Second Seno. This area has been subjected to chemical pollution originating from industrial activities for several decades, such as the steel plant ex-ILVA, the concrete factory Cementir, the Eni refinery station, and the Military Arsenal (Labianca et al., 2018). In addition, this basin has been strongly impacted by human activities such as wastewater discharge and mussel farming. It is also characterized by scarce water circulation, encouraging organic matter sedimentation and subsequent accumulation of pollutants in sediments (Cardellicchio et al., 2006). A particular characteristic of this basin is the presence of some submarine freshwater springs called “citri”. The pressures exerted on the Mar Piccolo have contributed to the deterioration of environmental matrices, as shown in **Table 1**.

Table 1. Pollution in the environmental compartments of the case study.

N.	Environmental compartment	Local pressures	Pollutants	References
1	Sediment	• Industrial activities (steel, oil, metals, varnishes, chemicals, paints), • Agricultural activities (run-off of chemicals), • Vessel traffic (Military Arsenal, fishing, mussel farming), • Illegal discharges of nutrients and contaminants, • Natural phenomena (e.g., absorption).	• PAHs: 56-36370 µg/kg • PCBs: 20-9391 µg/kg • Metals: As (3.77- 48 mg/kg), Cd, (0-1.5 mg/kg), Cu (9.1-172.7 mg/kg), Hg (0-16.7 mg/kg), Ni (23.33-60.66 mg/kg), Pb (24.42-272.54 mg/kg), V (25.67-95.61 mg/kg), Zn (38.51-602.89 mg/kg). (kg of dry solids).	(Todaro et al., 2019)
2	Marine water	• Vessel traffic (Military Arsenal, fishing, mussel farming), • Illegal discharges of nutrients and contaminants, • Natural phenomena (e.g., desorption, advection, diffusion of pollutants from/through sediments).	• PAHs: >0.2 pg/L • PCBs: 4652 pg/L • Metals: Cd (>0.3 µg/L), Cr (>0.3 µg/L) and Pb (>7.2 µg/L)	(ARPA PUGLIA, 2014)
3	Air	• Industrial gas emissions, • Natural phenomena (e.g., fall-out of pollutants).	• NOx: 5-15 µg/m^3, • SO_2: 4-12 µg/m^3 • PM10: 10-20 µg/m^3	(Trizio et al., 2016)

The ISPRA (ISPRA, 2010) characterization was adopted at the basis of the responses undertaken by local authorities, which in summary were expressed in limiting the use of part of the Mar Piccolo areas. For instance, after a monitoring plan started in 2011 by the Italian Local Health Authority for the evaluation of contamination by PCDD/F and DL/PCB in Mussel *Mytilus galloprovincialis* of Mar Piccolo and Mar Grande, the Italian ordinance nr. 1989 of 22 July 2011 prohibited harvesting and handling mussels in the First Inlet. To date, the Mar Piccolo has been included among the Italian most contaminated site of national interest with the Italian Ministerial Decree in 2000 (Ministerial Decree 10/01/2000, 2000) and is being studied by the Italian Government to choose the most suitable solution.

2.2. Structure of the holistic approach (eDPSIR)

The classic DPSIR framework considered a chain of causal links starting from “driving forces” which create “pressures”. The latter determine changes in the “states” of the environment (physical, chemical and biological situation), which can “impact” on targets such as ecosystems and human health, eventually leading to political or technical “responses” (e.g., indicators, policies and regulations) (**Fig. 2a**) (Borja et al., 2006). Differently, the eDPSIR provides new relationships between the different elements of the DPSIR. Its final goal is to select the most suitable remediation technology according to the specific objectives and preferences of a particular stakeholder, and based on technical, environmental, economic, and social criteria.

As the first step, all data and existing information needed to be identified and collected (**Fig. 2b**). The data must be reliable and as such comes from official sources (e.g., Environmental Protection Agency, universities,). Afterwards, three toolboxes are implemented, described in the following paragraphs. The three toolboxes act in synergy with the conventional DPSIR logic and follow the typical steps of a contaminated site remediation procedure (**Fig. 2c**). Several software packages are used, details of which can be found in section 2.3.

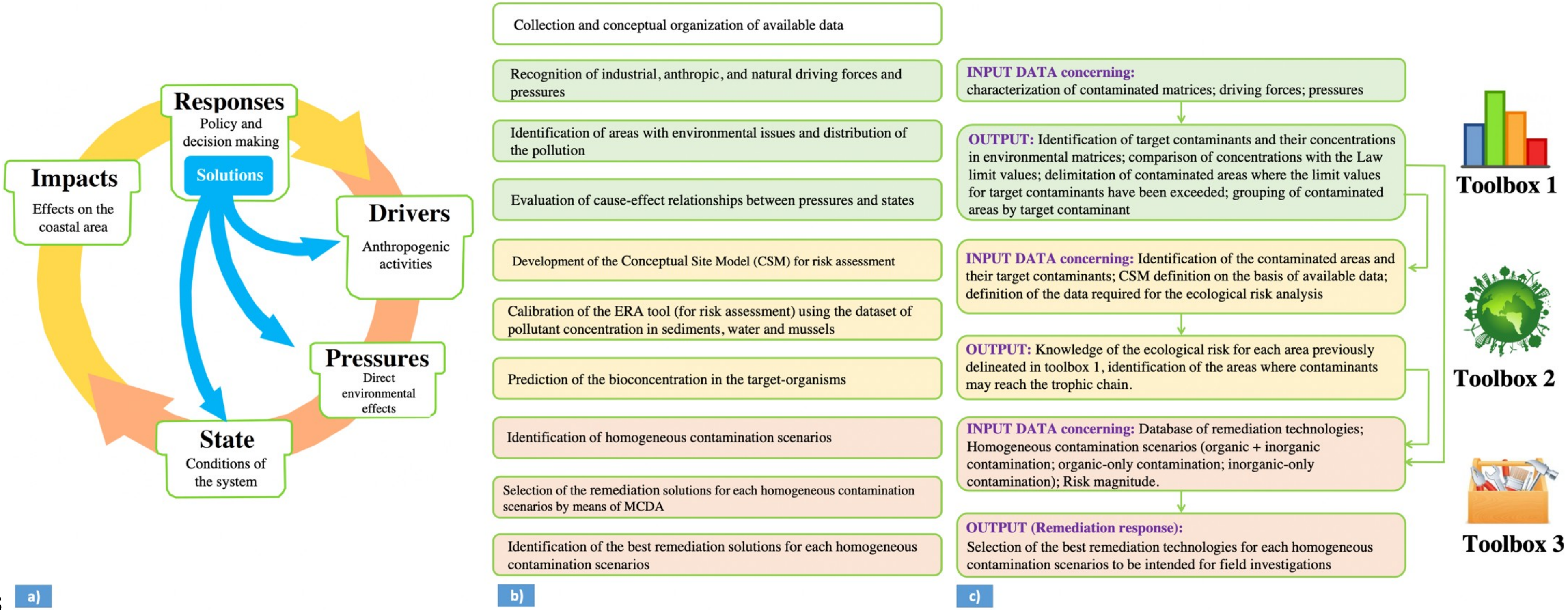

Responses
Policy and decision making
Solutions
Impacts
Effects on the coastal area
Drivers
Anthropogenic activities
Pressures
Direct environmental effects
State
Conditions of the system
a)
Collection and conceptual organization of available data
Recognition of industrial, anthropic, and natural driving forces and pressures
Identification of areas with environmental issues and distribution of the pollution
Evaluation of cause-effect relationships between pressures and states
Development of the Conceptual Site Model (CSM) for risk assessment
Calibration of the ERA tool (for risk assessment) using the dataset of pollutant concentration in sediments, water and mussels
Prediction of the bioconcentration in the target-organisms
Identification of homogeneous contamination scenarios
Selection of the remediation solutions for each homogeneous contamination scenarios by means of MCDA
Identification of the best remediation solutions for each homogeneous contamination scenarios
b)
INPUT DATA concerning: characterization of contaminated matrices; driving forces; pressures
OUTPUT: Identification of target contaminants and their concentrations in environmental matrices; comparison of concentrations with the Law limit values; delimitation of contaminated areas where the limit values for target contaminants have been exceeded; grouping of contaminated areas by target contaminant
INPUT DATA concerning: Identification of the contaminated areas and their target contaminants; CSM definition on the basis of available data; definition of the data required for the ecological risk analysis
OUTPUT: Knowledge of the ecological risk for each area previously delineated in toolbox 1, identification of the areas where contaminants may reach the trophic chain.
INPUT DATA concerning: Database of remediation technologies; Homogeneous contamination scenarios (organic + inorganic contamination; organic-only contamination; inorganic-only contamination); Risk magnitude.
OUTPUT (Remediation response): Selection of the best remediation technologies for each homogeneous contamination scenarios to be intended for field investigations
c)
Toolbox 1
Toolbox 2
Toolbox 3

Fig. 2. (a) Rationale, (b) framework of the holistic approach and (c) input/output data from each toolbox.

2.2.1 Toolbox 1

Toolbox 1 aimed at assessing the current state of environmental matrices by using recognized biological, physical, and chemical indicators, and consequently correlating states with pressures. Three steps were necessary: (i) recognition of industrial, anthropic, and natural driving forces and pressures, (ii) identification of areas with environmental issues and distribution of the pollution, (iii) evaluation of cause-effect relationships between pressures and states.

First of all, it is necessary to identify and collect all the industrial, anthropic, and natural driving forces and pressures through a review of academic and technical documents. The second step provides the spatial extent and magnitude of the contamination in a certain area, also identifying possible “hot-spots”. On this point, the guideline reference is site-specific. In the Italian case, it was the Italian Decree of the Ministry of Environment n. 173/2016 (Italian Decree n. 173/2016, 2016), which defined criteria and methodological procedures for classifying dredging sediment. The quantitative Weight of Evidence (WOE) model is used to integrate and weight sediment chemical measures. The WOE model considers the number of parameters exceeding threshold limits, the magnitude of these exceedances and the type of contaminant (Priority or Priority Hazardous substances, according to the Annex II of the Directive 2008/105/EC). The threshold values considered for the calculation of the chemical Ratio-to-Reference (RTR) correspond to the site-specific intervention values for marine sediments (ICRAM, 2004); in other cases, they may correspond with those defined by the local legislator. The Hazard Quotient for chemistry

(HQ_C) included in the WOE model is calculated according to Eq. 1, where an average RTR_W is obtained for all of the parameters with RTR ≤ 1 (i.e., below the normative limit), while the RTR_W is individually added into the summation Σ for those with RTR > 1 (Piva et al., 2011):

$$HQc = \frac{\sum_{f=1}^{N} RTR_w(j)_{RTR(f)\leq 1}}{N} + \sum_{k=1}^{M} RTR_w(k)_{RTR(k)>1} \qquad \text{(Eq.1)}$$

with N and M as the number of parameters with RTR respectively ≤ or >1, while j and k are indices allowing to repeat the calculation for N or M times. The values of HQ_C are assigned to one of six classes of chemical hazard: absent/white <0.7; negligible/green 0.7–1.3; slight/azure 1.3–2.6; moderate/yellow 2.6–6.5; major/red 6.5–13; severe/black >13. The chemical data from the ISPRA coring campaign in the period 2005-2010 (ISPRA, 2010) were employed in this analysis. The pollutants considered were metals and organic compounds. The sample points are shown in **Fig. S1** in the SI and the coring depths were 0-10 cm, 10-30 cm, 30-50 cm, 100-120 cm, and in some cases 180-200 cm, 280-300 cm. The first two steps made it possible to delineate the contaminated areas and identify the target contaminants, in line with the remediation procedure. The third step considers a multivariate statistical analysis useful to describe the large dataset, which aims to identify correlations among variables, grouped in clusters. Principal Component Analysis (PCA) and Cluster Analysis (CA) are used for this purpose, together with a correlation analysis, in order to find information about the existing site-clusters with similar pollution characteristics and to identify the most important discriminant contaminants (variables) within the same cluster. In our case, the statistical analysis was carried out on the total matrix consisting of 1023 samples 3 m deep and 20 variables, including moisture content, granulometry, metals, metalloids, and nutrients) (ISPRA, 2010). The adoption of the above statistical methods required to establish well-defined assumptions. In our case, it was hypothesized that the excessive presence of nutrients and organic matter in seawater could act as a carrier for many contaminants concentrated in the fine fraction of sediments with a high percentage of organic matter. Therefore, high concentrations of metals may be related to both organic matter and nutrients in the water column.

2.2.2 Toolbox 2

Having clear the current state of environmental matrices, the Ecological Risk Assessment (ERA) is a useful tool to determine the adverse (ecological) effects occurring as a result of exposure of a biological community to potential stressors. At first, it is necessary to develop a Conceptual Site Model (CSM) with the goal of understanding how contaminants migrate from their sources and the pathways through which migration and exposure of potential human or environmental receptors can occur. Two steps are foreseen (i) calibration of the bioaccumulation model using a dataset of pollutant concentration in sediments, water, and mussels; (ii) prediction of the bioconcentration in the target-organisms, using a full dataset of a previous coring campaign (ISPRA, 2010). In this study, the Mussel *Mytilus galloprovincialis* was considered as bio-target in the Arnot and Gobas model, being the most common species in the Mar Piccolo due to the intensive mussel farming activity. Eq. 2 shows the bioconcentration process (Arnot and Gobas, 2006):

$$\frac{dC_B}{dt} = (k_1 C_{WD}) - (k_2 + k_E + k_M + k_G)C_B \qquad \text{(Eq. 2)}$$

where C_B is the chemical concentration in the organism (g/kg), *t* is a unit of time (1/d), k_1 is the chemical uptake rate constant from the water at the respiratory surface (l/kg d), C_{WD} is the freely dissolved chemical concentration in the water (g/l), and k_2, k_E, k_M, k_G are rate constants (1/d), representing chemical elimination from the organism via the respiratory surface, fecal egestion, metabolic biotransformation, and growth dilution, respectively.

The data employed in the first step derived from the sampling campaign to characterize water, sediments and biota concerning the convention of 28/05/2013 between the Special Commissioner of the Italian Government and the Apulia Regional Environmental Agency. **Table S1** in the SI shows all the chemo-physical information employed in the first step, used as input data in the software in order to calibrate the model. The target contaminants investigated in this analysis were Polycyclic Aromatic Hydrocarbons (PAHs) although the same approach can be extended to any other type of pollutants.

2.2.3 Toolbox 3

The last toolbox aimed at connecting the responses with the driving forces, pressures, impacts, and states with the final goal to identify the most suitable remediation intervention, in terms of applicability and social, political, and technological aspects. The openness to all these aspects was due to the fact that in socially relevant environmental problems, as in the case of the Mar Piccolo, the decision-maker has to find the best solution from a technical point of view, motivating the reason for the selection and mainly taking into account local economies.

Based on the results of the first toolboxes, three different scenarios of contamination can be considered: SC1 with metals, PAHs and PCBs present in the same concentration (mixed contamination); SC2 with concentration of metals higher than PAHs and PCBs (prevalent inorganic contamination); SC3 with concentration of PAHs and PCBs higher than metals (prevalent organic contamination). For each contamination scenario, the framework for selecting the technological remedial alternatives consisted of two phases: (i) Multi-Criteria Decision Analysis (MCDA), aimed at evaluating the three most suitable technologies; (ii) application of a coaxial matrix for each technology recognized in the previous step, with the goal of identifying the best technology.

The MCDA (OECD-JRC, 2008) offered a scientifically sound decision framework and entailed the following steps: (i) preliminary screening of potential remedial technologies (so-called alternatives); (ii) identification of the selected alternatives and evaluation criteria (qualitatively and quantitatively based); (iii) construction and normalization of the alternative matrix; (iv) construction of the composite indicator (which was indicated as Preference Index - PI); (v) identification of the optimum alternatives.

The initial panel of remediation technologies was identified by a technical working group (TWG) through a critical analysis of technical and scientific reports (ACE, 2014; FRTR, 2002; Hasegawa and Rahman, 2016; SMOCS, 2012; UNIDO, 2007) (**Fig. S2**). The criteria used to evaluate the technologies were classified in applicability and technological aspects (**Table S2**). The criteria were defined on the basis of current technical-scientific literature and were all independent of each other; more information on the grade assignable to each criterion is shown in **Table S3** of Appendix. Clearly not all criteria weighed the same; according to Sabia et al. (2016), the weighing of the criteria requires the definition of the priority order. The priorities adopted by the TWG are shown in **Table S2**. Then, each criterion was given a weight, according to the relation with all other criteria, and qualitative criteria were transformed into quantitative for better homogenization and comparison. The Paired Comparison Technique (PCT) (Goletsis et al., 2003) was used for a pairwise comparison. At this point, the Matrix of Alternatives (MOA) was drawn up with the potential technologies in the rows and the evaluation criteria in the columns. A normalization of the matrix was subsequently carried out according to the max/min method (Eqs. 3 and 4):

$$x_{\bar{ij}} = x_{ij}/\mathrm{Max}(x_j) \qquad \text{(Eq. 3)}$$

$$x_{\bar{ij}} = \mathrm{Min}(x_j)/x_{ij} \qquad \text{(Eq. 4)}$$

where, x_{ij} is the performance of the alternative i-th (each remediation technology) with respect to the j-th indicator (each evaluation criterion), w_j the weight of each indicator, $x_{\bar{ij}}$ the normalized value of x_{ij} calculated with Eqs. 3 and 4 if the criterion is to be maximised or to be minimised, respectively. As result, all the values of the normalized matrix were in the range [0, 1].

Through the Simple Additive Weighing (SAW) method (Afshari et al., 2010), the MOA was resolved, multiplying each element of the matrix with the weight of the corresponding column. The PI of the single alternative was calculated following Eq. 5:

$$PI_i = \sum_{j=1}^{m} x_{\bar{ij}} \cdot w_j \qquad \text{(Eq. 5)}$$

where w_j represents the weight for each evaluation criteria.

At the end, the best technological alternatives were identified with the highest PI, according to the scenario considered, and distinguishing between *in-situ* and *ex-situ* alternatives. Lastly, coaxial matrices (Ruppert et al., 2015) put in relation and in a logical sequence, respectively: (i) project actions, (ii) impact factors, (iii) environmental components, and (iv) potential environmental and human risks. Drawing up different evaluation analysis sheets, it was necessary to quantitatively assess all possible impacts of each remediation project action using the range [-4, +4], with -4 for the worst system alteration and +4 for the best one. Summing all the impact values and converting them into a scale of 100, it was possible to quantify and compare all the impacts of every single remediation project.

2.3. Software used in the proposed methodological framework

The Arnot and Gobas model (Arnot and Gobas, 2004) was considered; through the Aquaweb software, site-specific evaluations of bioconcentration/bioaccumulation factors in organisms of aquatic food webs from chemical concentrations in water and sediments (available at https://arnotresearch.com/aquaweb/), were conducted. The QGis software was used for data visualization (available at https://www.qgis.org/it/site/forusers/download.html). Lastly, three different types of software were used to conduct multivariate analyses: The Unscrumbler software and SIMCA for the Principal Component Analyses (PCA) and Statistica10 for the Cluster Analyses (CA). The knowledge of these specialist tools was fundamental and preparatory to the understanding of the three developed toolboxes.

3. Results

3.1. A complex environment: organization of available data

Before presenting the results of the 3 toolboxes, it was essential to organize the massive amount of available data. Researchers investigated both the economic aspects, linked to the activity of shellfish farming, and the hydrogeological aspects, and showed the complexity of this coastal system. Numerous studies concerning multiple aspects have been carried out; the Mar Piccolo is undoubtedly a complex system, an accurate schematization of it is surely the most important starting point towards remediation (**Fig. 3**).

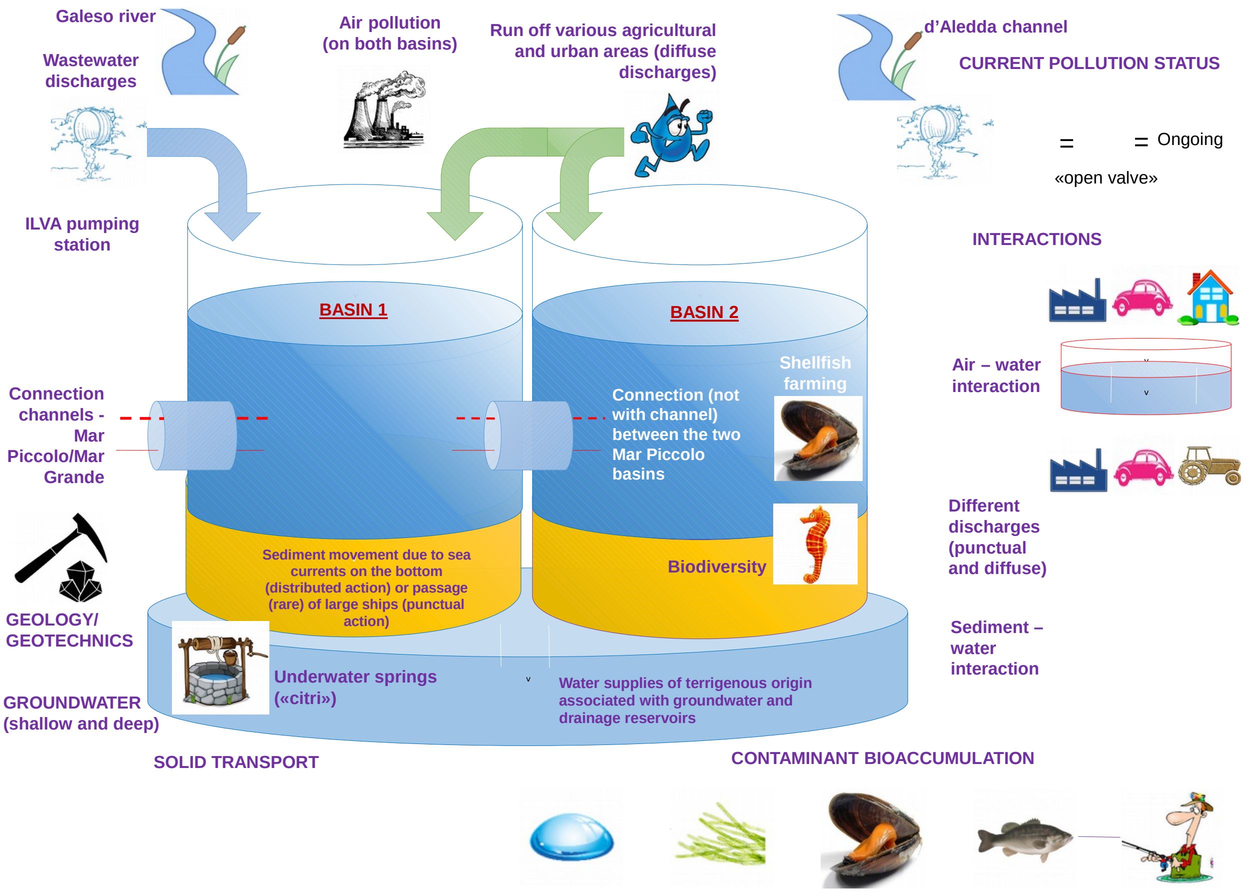
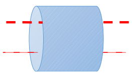
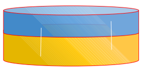


Fig. 3. Schematization of the main elements of the Mar Piccolo system.

The two basins are immersed in saturated soil and at some spots in contact with the water table. The two basins are connected to each other and to the open sea, the Mar Grande. There are numerous pressures from point discharges of wastewater and watercourses (the Galeso River and the D'Aiedda channel) to the surface run-off as a result of rain. There is also the presence of highly impacting activities, such as shipyards and the military arsenal. Several organic/inorganic pollutants are present in sediments (**Table 1**); interstitial and free waters are instead affected by wastewater discharges, characterized by non-negligible concentrations of organic substances (Biochemical Oxygen Demand, Chemical Oxygen Demand) and nutrients, and other contaminants such as PAHs and PCBs. **Table 2** summarizes most of the information available to date.

Table 2. Milestones achieved on the basis of current literature.

Symbol[a]	Aspect	Main considerations	References
	Movement of sea currents in Mar Piccolo – Mar Grande connection channels	On average the current is directed towards the Mar Piccolo (entering) in the deeper layers, while in the more superficial layers the current is directed towards the Mar Grande (outgoing).	De Pascalis et al. (2015); Armenio et al. (2016); De Serio e Mossa (2016)
	Interaction between sediment and bottom sea currents (erosion and accumulation phenomena).	The values of the maximum tangential load (responsible for erosion) at the bottom of the seabed are mainly located in the Mar Piccolo - Mar Grande connection channels (Canale Navigabile, Canale Porta Napoli) and at the ILVA water pumping station (which brings water to the industrial area). A tendency towards sediment deposition has been observed in the remaining parts of the Basin I and in the Basin II.	De Serio et al. (2018)

	Wastewater discharges	Mar Piccolo is subject to both private and public discharges. A total amount of 100,000 equivalent inhabitants is estimated to be discharged into Mar Piccolo. 85% of the inlet flow rate is discharged into the Basin II, with an amount of organic matter equal to 6.7 t/d of BOD_5. The daily release of nitrogen and phosphorus into the basin has been quantified as 17.2 t/d and 0.3 t/d, respectively.	Cardellicchio et al. (1991); Caroppo et al. (1995); Scroccaro et al. (2004)
	Run off of agricultural and urban areas in the Mar Piccolo catchment area (diffuse discharges)	The hydrographic grid coincides with the Galeso basin and its main tributaries with 60 km^2 surface. It also includes the industrial area of Taranto. The basin is subject to flooding and shows an erosive character, resulting in solid transport from the Galeso river basin.	Blonda et al. (2014).
	Geology and geotechnics	Geology: Holocene deposits between 0.5 m and 11 m; Recent alluvial deposits between 1 m and 20 m; Terraced marine deposits between 5 m and 30 m; Sub-Apennine clays from 10 m to 65 m; Gravina limestones with thickness less than 2-3 m; Mesozoic limestones from -20 m to -80 m depth, decreasing towards the Gulf of Taranto. Geotechnics: Clay percentage increases with the depth (from 11 to 12 m of seabed) and reduces that of sand, while the silt is maintained constant; Bioclasts (with dimensions greater than 1 mm) are an element of non-homogeneity of the clayey-lime matrix, impacting on the regularity of the mechanical characteristics. The natural water content and plasticity index show a "fluid" behaviour of the material depending on chemical characteristics of the interstitial fluid (mix of sea water, organic substances, contaminants).	Blonda et al. (2014); Vitone et al. (2016); Valenzano et al. (2018); Sollecito et al. (2019)
	Biodiversity	The Mar Piccolo is a "transition" environment (WFD, 2000/60 EC). There is a peculiar vegetal and animal biodiversity, mainly composed of nitrophilic macroalgae and filter organisms. The high biodiversity found (in number and species) together with the high self-regulating and reactive capacity of the system, are indicators of the great potential for recovery of the area from a naturalistic and environmental point of view. There are also protected species.	Prato and Biandolino (2005); Blonda et al. (2014)

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	Water supplies of terrigenous origin associated with groundwater and drainage reservoirs	The deep aquifer located in the Altamura limestones drains the water coming from an upstream hydrological basin of 900 km^2 and undergoes a rapid decrease in piezometric heights (piezometric cadence of 2‰) causing the formation of terrestrial (Galeso, Lavandaia, Marangio, Battentieri, and Riso) and underwater springs (among the best known are the citri Galeso and Citrello in Basin I, Le Copre, Calandrea, and Mascione in Basin II). Limited knowledge is available about surface aquifers. No information is available on the interconnections between deep and superficial aquifer. This situation is made even more complex by the consistent intrusion of seawater.	Blonda et al. (2014).

The complexity described above makes it possible to evaluate how remediation should take place and how to cope with the existing sources of contamination, either by removing them or by regulating them. Consequently, at the same time as remediation, the decision-maker decides to act on the driving forces and pressures involved.

3.2. Towards remediation

3.2.1 Toolbox 1: state of the environment and role of discharges in sediment pollution

The literature on the Mar Piccolo identified the driving forces as well as the pressures. With 195,279 inhabitants in 2019, Taranto is the most populous city in the Mar Piccolo catchment area. Different types of agricultural areas fall into the Mar Piccolo catchment basin (vineyards, olive groves, and arable crops are the most abundant), covering the 55% of the total agricultural area of the basin. ISTAT data revealed an increase of agricultural fertilizers employed between 2003 and 2008 and phytosanitary products between 2013 and 2016 (ISTAT, 2018) and, assuming run-off as one of the main impacts, pollutants and nutrients were brought into the Mar Piccolo. The industrial area on the west side is responsible for high impacts in terms of pollutant production and distribution (steel factory, oil refinery, and cement factory). Severe pressures can be attributed to the presence of the Italian Navy shipyard with its dry docks on the south side of the first bay as well as to intensive mussel farm production (with 30,000 tons/y) and the fishing-boat activity in both bays. Nine sewage discharge pipes and small rivers together with D'Aiedda channel drained nutrients into the basin (Cardellicchio et al., 2007). The D'Aiedda channel discharges the treated wastewaters of 8 municipalities into the second bay (Scroccaro et al., 2004). About 18,272 m^3/d are released into the Mar Piccolo, the 85% of which into the second bay. The demography, agriculture, and industry were considered as the main driving forces. The corresponding pressures were the discharges of nutrients and contaminants, pollution in groundwater and in air. The state of the environment, on the other hand, was characterized mainly as marine sediment, seawater, and biodiversity; the latter was not presented in this study. The calculation of the HQc index allowed visualizing the map of chemical hazard for the marine sediments in a GIS environment at different depths from the sea floor (**Fig. 4a-f**).

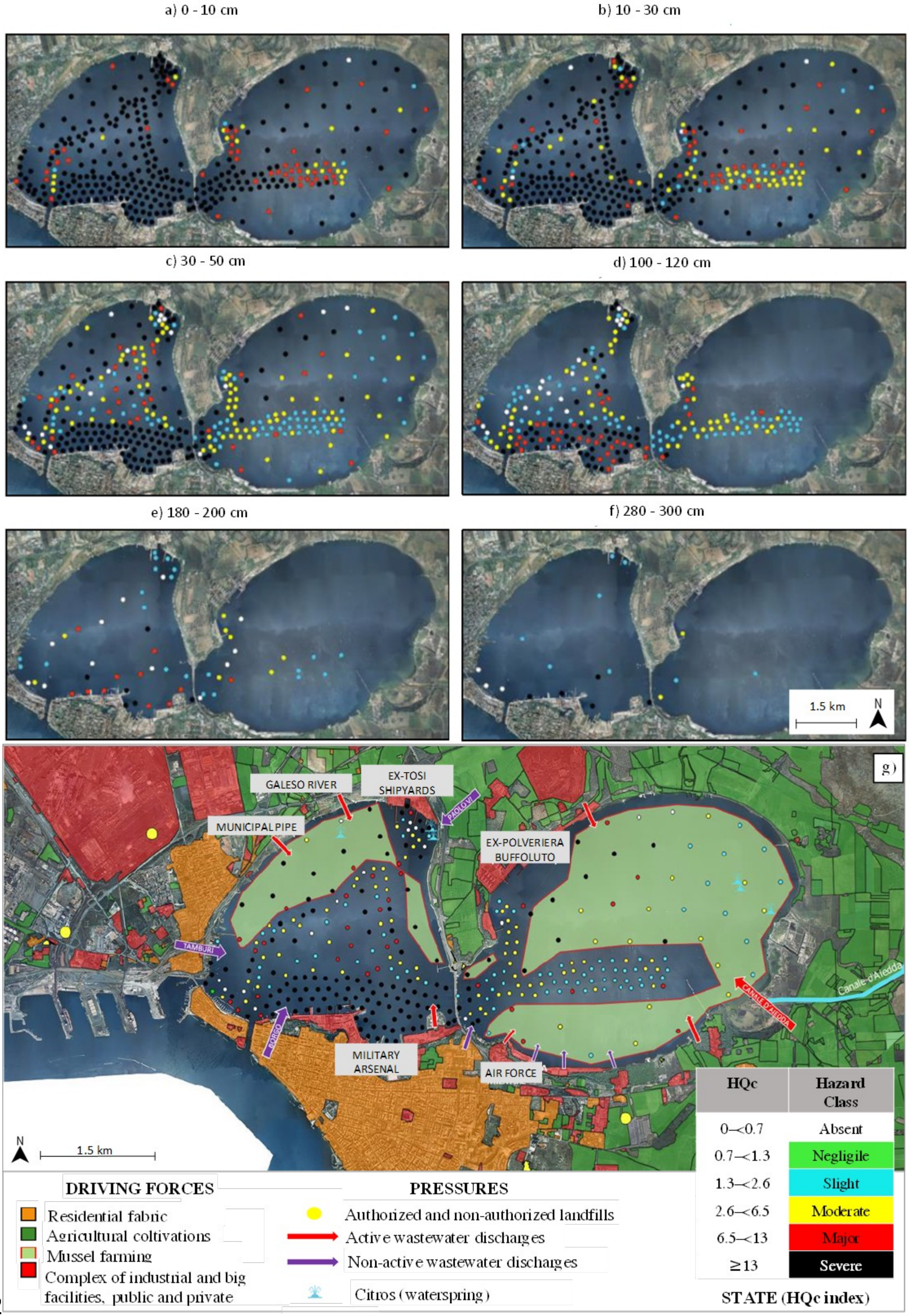
a) 0 - 10 cm
b) 10 - 30 cm
c) 30 - 50 cm
d) 100 - 120 cm
e) 180 - 200 cm
f) 280 - 300 cm
1.5 km
N
g)
GALESO RIVER
EX-TOSI SHIPYARDS
MUNICIPAL PIPE
EX-POLVERIERA BUFFOLUTO
TAMBURI
MILITARY ARSENAL
AIR FORCE
Canale d'Aiedda
HQc
Hazard Class
0–<0.7
Absent
0.7–<1.3
Negligile
1.3–<2.6
Slight
2.6–<6.5
Moderate
6.5–<13
Major
≥13
Severe
STATE (HQc index)
DRIVING FORCES
Residential fabric
Agricultural coltivations
Mussel farming
Complex of industrial and big facilities, public and private
PRESSURES
Authorized and non-authorized landfills
Active wastewater discharges
Non-active wastewater discharges
Citros (waterspring)

Fig. 4. HQc chromatic maps showing sediment chemical hazard at different depth (a) 0-10 cm, (b) 10-30 cm, (c) 30-50 cm, (d) 100-120 cm, (e) 180-200 cm, (f) 280-300 cm; (g) D-P-S map of toolbox 1.

It was possible to observe that the first layers of the sea bottom were the most polluted (0-10 cm, 10-30 cm, 30-50 cm), showing a spread contamination in both inlets. The area of the Marine Arsenal appeared to be the most critical zone, since even deep layers (100-120 cm, 180-200 cm, 280-300 cm) recorded high values of the HQc index. The two inlets presented a macroscopic difference, with more serious, widespread, and deep contamination in the First Bay.

The approach adopted in Toolbox 1 allowed understanding the quantitative role of each contaminant in the definition of the HQc index. For this purpose, histograms were elaborated for each sub-area visible in **Figs. S3-S26** in the SI. The interpretation of the histograms made it possible to identify various results, summarized in **Table S4**.

The map in **Fig. 4g**, which represents an average of the layers 0-100 cm, visually links main pressures with environmental status. The histograms for each sub-area (Figs. S3-S26) revealed the main pressures that induced that contamination. Lastly, the multivariate analysis allowed identifying possible cause-effect relationships between pressures and states. Considering the correlations between nutrients and metals (**Figs. S27-S28**), results showed how the excessive presence of nutrients and organic matter in the marine water could act as carrier for many contaminants in the fine fraction of sediments, the latter characterized by high percentage of organic matter. It was possible to identify two macro clusters: (i) TOC (Total Organic Carbon), As, Cd, Zn, Hg, Pb, Cu, clay and gravel; (ii) P_{tot},

N_{tot}, Cr, Fe, Al, V and Ni. While in the first cluster TOC was considered as the responsible correlating element, in the second cluster the responsible ones were the nutrients (N_{tot} and P_{tot}). Furthermore, high concentrations of Cr, V, and Ni showed high correlation, underlining their apparently natural presence in surficial layers.

These findings through statistical procedures confirmed the validity of the assumptions made in Toolbox 1, highlighting the role of discharges on sediment pollution. Mali et al. (2017) corroborated our results and underlined that the nature and origin of organic matter within different layers, the rates of dilution by terrigenous sediments, the grain size fractions, the aggregation phenomena, and the original composition of the sediment parent rocks can influence the contaminant pattern as the main controlling factors.

3.2.2 Toolbox 2: quantifying bioaccumulation

Toolbox 2 quantified the impact on humans based on the conceptual site model in **Fig. 3**.

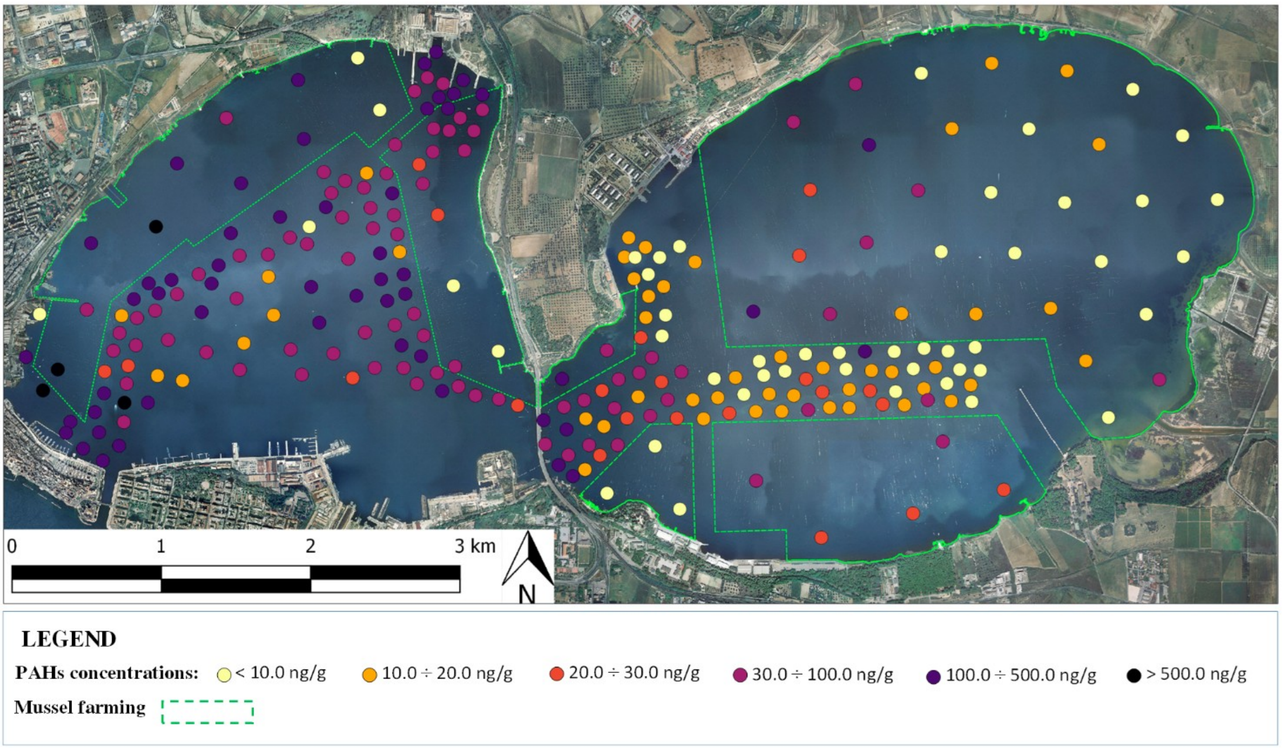

Fig. 5. ERA map showing the risk of bioaccumulation modeled in the bio-target.

The CSM showed how the contamination of the seawater was attributed to urban/industrial discharges/deposition as well as the runoff of the surrounding soil. There was a supply of spring water from the bottom of the Mar Piccolo, while aeriform pollutants could pass from air to water. Contamination could reach human via trophic chain. The quantification of such impacts on human included the selection of the target contaminant; the analysis was conducted considering only PAHs, although the same could be replicated in the case of metals and PCBs, which were abundant in the study areas. All the site-specific data input, together with the PAH contamination values in sediments and water, were entered in the software Aquaweb. A good fitting of the calibration process (R^2 = 0.87) between the PAH concentration in the bio-target (mussel) sampled and modeled was achieved as visible from

Fig. S29.

This approach was subsequently extended to the entire case study and, starting from the concentration values in sediments and water, it was possible to predict the bio-concentration in mussels present in both inlets. The results showed how the areas used for the mussel farming recorded high modeled values of contamination in the bio-target (**Fig. 5**), highlighting a hazardous threat to the trophic chain. According to the Commission Regulation (EU) No 835/2011 of 19 August 2011, amending Regulation (EC) No 1881/2006, as regards maximum levels for PAHs in foodstuffs (sum of benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene and chrysene), the maximum concentration acceptable in mussels is 30 ng/g. Peaks higher than 100 ng/g were recorded in the First Inlet especially on the west shore and in the central area. As an example, in 2011 mussel farming in the First Inlet was banned following detection of PCBs and dioxins in the mussels for human consumption (ASL TA, 2011).

Toolbox 2 has, therefore, quantified the hazard related to the contamination of environmental matrices by PAHs. As reported in Tongo et al. (2017), chronic intake of toxic organic compounds has adverse impacts on human and an excess of threshold values indicates potential health risk from consumption.

3.2.3 Toolbox 3: selection of technological remediation actions

Before presenting the results of Toolbox 3, it is interesting to note that the current responses adopted by local authorities included the limitations on the use of marine areas and at the same time regularizing the pressures on the environment. The results shown below are valid if and only if pressures are eliminated and contained. The resolution of the matrix of alternatives (MOAs) was carried out for each scenario of contamination. **Figs. S30-32** showed the resolution of SC1, SC2 and SC3, respectively. The highest PI score, and consequently, the best technology identified was Amendments, for all the three scenarios investigated (**Table S5**). Amendments are represented by any material (e.g., activated carbon, organoclay, apatites, etc.) that may interact with the contaminated sediment/soil enhancing the pollutant sequestration and degradation. In the scenario SC1, where the contamination was given by metals, PAHs, and PCBs simultaneously, the PI index pointed out *ex-situ* solution (Vitrification); in the scenarios SC2 and SC3, the PI index highlighted the Assisted Natural Attenuation (ANA) as *in-situ* solution. The first five positions for the *in-situ* technologies, and in all the scenarios evaluated, were: (1) Amendments, (2) Assisted Natural Attenuation, (3) Monitored Natural Attenuation, (4) Containment barriers, and (5) Passive capping. For the *ex-situ* technologies, vitrification appeared to be the most promising alternative in all scenarios. Solvent extraction and thermal desorption were the second or third position depending on the scenario, while mechanochemistry and confined disposal facility reached the fourth and fifth position, respectively, in all the three scenarios considered.

It is noteworthy that the excavation and disposal option, together with the application of nanoremediation technologies, represented the last choices to undertake. Although some positive outcomes are present in the literature (Xue et al., 2018), nanoremediation requires a robust preliminary field-scale study to investigate the treatment feasibility (Lofrano et al., 2017).

The adopted multi-criterial approach has allowed integrating a diversity of criteria in a multidimensional way and in a large variety of contexts.

The second phase of Toolbox 3 consisted of the development of three coaxial matrices for the best treatments identified through the MCDA analysis. The best three technologies identified through the multicriteria approach were: (i) reactive capping, as an *in-situ* treatment with the use of amendments, (ii) a train-treatment based on dredging plus thermal desorption plus stabilization/solidification (S/S), as *ex-situ* approach, and (iii) assisted natural attenuation. To achieve this, it was necessary to define the project actions, which vary for each technology, the impact factors, the environmental components, and the relative potential environmental and human health risks. The coaxial matrices (**Figs. 33S-35S**), together with the evaluation matrices, allowed identifying and evaluating quantitatively the activities responsible of environmental disturbance for each project action. A quantitative evaluation sheet was developed for each project action and subsequent impacts and environmental components and alterations. An example of an evaluation matrix is shown in **Table S6** in the SI.

All the scores were summed and converted in a scale of 100 for comparison. The activities with the highest negative scores would take the most impactful actions, and vice versa. The sum of the total impacts for each project action proved to be a useful global information on the remediation treatment itself, easily comparable with the other technologies. The results identified Assisted Natural Attenuation as the best solution in terms of environmental impact and compatibility (**Fig. 6**). ANA recorded a value of impacts equal to 214, whereas reactive capping and train treatment reached 238 and 375, respectively.

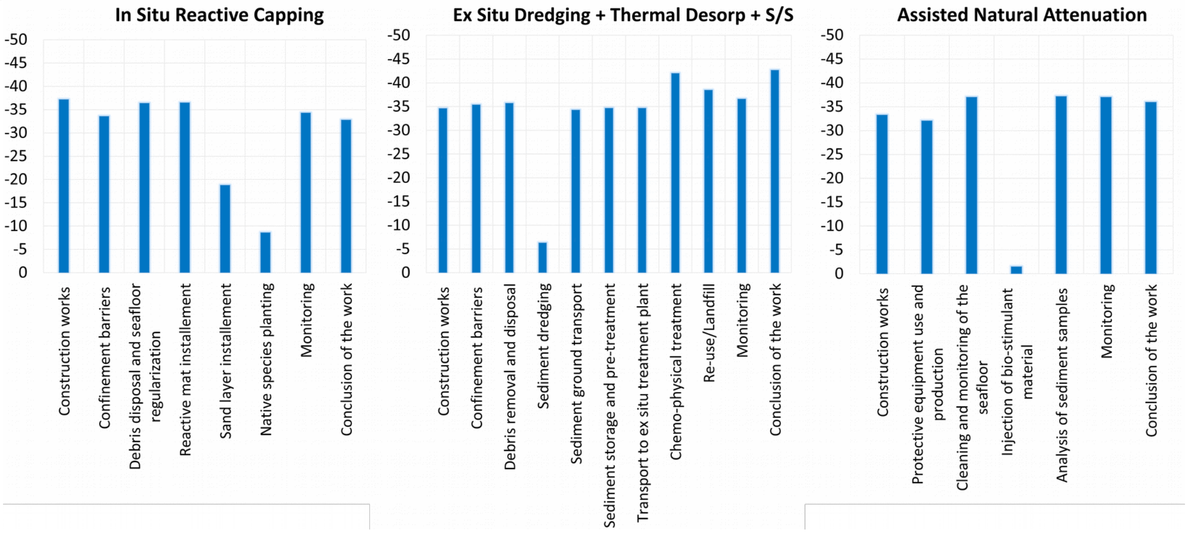

Fig. 6. Comparison of final scores from the coaxial and evaluation matrices for the three treatments considered.

This systematic approach allowed identifying and quantifying the total impacts related to remediation treatments, which permitted reducing contamination in environmental matrices and still involved impacts and repercussions. Once the most suitable remediation technologies have been identified, they can be applied to the contaminated areas identified with Toolbox 1 without neglecting the pressure that should be contained.

4. Discussion

This study deals with what would have been done without eDPSIR and what is the added value of implementing eDPSIR. The DPSIR was characterized in a broader sense by incorporating plans and programs with the intent to place restrictions on the use of the site and/or containing the pressures. The eDPSIR, instead, guided the decision-maker in the selection of remediation technologies.

Concerning the correlation between D-P-S, most of previous studies applied the DPSIR framework qualitatively, with a non-depth, statistically based assessment of the roles of P on S (Lofrano et al., 2015; Skoulikidis, 2009; Zebardast et al., 2015; Zhang and Xue, 2013). Other authors used a set of key indicators, such as Environmental Assessment Criteria (EAC) (Cinnirella et al., 2013), Ecological Effect Index (EEI) (Lu et al., 2019), and those within the Strategic Environmental Assessment (SEA) (Cheng et al., 2011), but the investigation of cause-effect relationships was still missing. In contrast, starting from the site-specific sources of pollution, Toolbox 1 in this study clarified the state of contamination in marine sediments, with specific correlations with pressures (see the histograms of **Figs. S3-S26**). The multivariate analysis has proven to be a useful tool to assess the correlation between contaminants in water and sediment (Mali et al., 2017). However, it was essential to make science-based hypotheses, which then needed to be verified. This toolbox revealed the target contaminants and the extension of the contamination, in line with a remediation procedure. Other assumptions can be made using the same method.

With reference to the S-I link, the literature focused mainly on the definition and then application of key indicators to quantify impacts on the environment and on human (Barjoveanu et al., 2010). However, what makes the impact assessment accurate is the CSM. Toolbox 2 aimed to standardize this phase. As for toolbox 1, it was necessary to define the hypothesis to be subsequently verified: the presence of bioaccumulation phenomena of pollutants, moving them from sediment and water to mussels, creates serious risks for human consumers. Also, toolbox 2 allowed highlighting the areas where contaminants may reach the trophic chain.

With reference to closing the cycle through D-P-S-I-R linkage analysis, Toolbox 3 provided new *modus operandi* on how to select the optimal remediation technologies. First of all, it is important to be aware that a complex environmental problem is being addressed; this is not always clear to decision-makers. Such a complex problem must include a multi-disciplinary and participatory approach, which can be extended to all stakeholders in the area. Stakeholders participation is essential to make the whole decision-making process traceable first and then to take into account the needs of the area (De Feo and De Gisi, 2010). A remediation intervention can be seen as a new development for local economic activities and aspects to be considered among evaluation criteria. While the use of multi-criteria analysis to address complex environmental problems is well established, the elements of MCDA needed to be set up. The current references (ACE, 2014; FRTR, 2002; Hasegawa and Rahman, 2016; SMOCS, 2012; UNIDO, 2007) provided only preliminary information for defining the initial panel of remediation technologies. The definition of the assessment criteria and their priorities, together with the weighting vector, had to take into account multiple aspects, ranging from the technological ones related to remediation technologies to the social ones.

The eDPSIR goes in the direction outlined by Lewison et al. (2016) that highlights the presence of qualitative relationships, limited interdisciplinarity, the use of DPSIR as a cognitive tool, the need to develop decision support tools, as well as the need to include local stakeholders in the decision-making process. The eDPSIR could allow overcoming these bottlenecks. The last aspect to highlight is the eDPSIR generalization. **Table 3** shows the synoptic framework enabling the eDPSIR holistic approach to be extended to other territorial contexts.

Table 3. Starting conditions summary for the eDPSIR application.

Starting conditions	
Type of data to be determined for the "Driving Forces" and their source:	It is necessary to have information about all the possible activities/phenomena that led to pollution.
Type of data to be determined for the "Pressures":	Starting from the driving forces, the related produced pressures are identified (emissions, waste, discharges, etc.) in quantitative terms.
Type of data to be determined for the "States":	Having clear sources and impacts of pollution, it is fundamental to understand the states of the environmental compartments in order to recognize which are the areas most impacted (concentrations of pollutants in sediments, water, and air). In order to make this step more reliable, homogeneous data should be used (e.g., data on chemical characterisation of sediments on samples taken on the same day and with the same sampling method).
Type of data to be determined for the "Impacts":	The aim in this case is to diagnose the phenomena involved from contaminated matrices on targets such as ecosystems and humans (through risk assessment

	analyses). Impact assessment methodologies should be selected on the basis of data availability.
Type of data to be determined for the “Responses”:	The responses can be programmatic and technological. In this study, emphasis was placed on both. Technological responses include remediation; programmatic responses relate to the need to control/limit ongoing sources of contamination.
Software/tools to be used:	Aquaweb, QGis, Simca, Unscrumbler, Statistica10
Other methodological tools	WOE criteria, Arnot and Gobas model, coaxial matrices, multi-criteria analysis
References for remediation technologies	See the Manuscript, sections 2.3.3 and 3.2.3, and the Appendix (Supplementary material).
Community involvement	It is allowed, directly in the phase of weighing the criteria for the assessment of remediation technologies.

5. Conclusions

Based on the findings of the Mar Piccolo of Taranto case study, the eDPSIR has proven to be a valuable tool to support decision makers in choosing the technological response for the remediation of heavily contaminated coastal areas. The introduction of the three toolboxes, each with its own specific features, made it possible to investigate and quantify cause-effect relationships. Considering the toolbox 1, "*state of the environment and role of discharges in sediment pollution*", the application of the Hazard Quotient-Chemical index on a large data set allowed identifying the extent and magnitude of contamination for target organic (PAHs and PCBs) and inorganic contaminants. The multivariate statistical analysis ~~Principal Component Analysis~~ proved to be a valuable support to the understanding of the dynamics according to which the excessive presence of nutrients and organic matter in seawater could act as a carrier for many contaminants concentrated in the fine fraction of sediments with a high percentage of organic matter, providing useful information to the decision-maker in formulating programmatic responses, such as containing/controlling pressures. Considering Toolbox 2, "*quantifying bioaccumulation*", it made it possible to quantify the hazard of contaminated marine sediments and highlighted how contaminated sediment and water can pose a serious threat to humans and wildlife, which may come into contact and absorb toxic and carcinogenic compounds through the food chain. Toolbox 2 allowed visualizing the areas where contaminants may reach the trophic chain. The most site-specific aspect in Toolbox 2 was the definition of the conceptual model linking contamination sources with migration paths and natural and human targets. As to Toolbox 3, "*selection of technological remediation actions*", the application of a MCDA first and coaxial matrices then allowed identifying the Assisted Natural Attenuation as one of the best solutions starting from a panel of 50 remediation technologies. The MCDA was characterized by transparency and replicability, which are fundamental characteristics in the case of complex environmental and social problems. As a final consideration, the three toolboxes have proven to be an added value to existing literature. They have made the DPSIR as an environmental decision support system rather than a cognitive tool of the environmental phenomena in a system. Since the proposed toolboxes are hypothesis-based, the eDPSIR presents itself as a tool open to new formulations to be verified.

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Credit author statement

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Declaration of competing interest

The authors have no conflicts of interest to declare.

Appendix A. Supplementary data

The following is the Supplementary data to this article:

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