

multi-Risk sciEnce for resilientT commUnities undeR a changiNgclimate

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## TECHNICAL REFERENCES

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## ABSTRACT

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Among the research lines of WP5 of VS4, of the RETURN Project, there is the development of quantitative and probabilistic methodologies for multi-risk assessments to support the identification of effective and economically sustainable strategies to mitigate the impacts caused by sediment handling in marine coastal areas and ports affected by maintenance and capital dredging or reclamation operations. In this case, sediments can represent a wide range of risk sources, and their possible interactions may generate cascading effect scenarios. **Task 4.5.3** addresses the theoretical development of the multi-risk approach developed specifically for the management of dredged sediments and their handling. To date, we follow the regulatory guidelines based on two different strategic approaches.

- The first concerns the results of the ecological analysis based on the quality classification of the sediments, an analysis characterizing from an Eco toxicological and chemical point of view. In this case, good quality sediments can be immersed back into the sea; on the contrary, the sediments with the worst class must follow different management paths, including storage in confined disposal facilities and, eventually, disposal in specialized landfills.
- The second approach, referring to explicit contaminated areas, is based on environmental risk analysis: in this case, the sediments that are contaminated, like the soils, must be reclaimed to be recovered, to bring the environmental contamination under the so-called risk threshold.

In this scenario, multi-risk analysis would make it possible to develop a useful decision support system aimed at defining the best management way. For example, by coupling the ecological evaluations with the sanitary-environmental ones, it is possible that the sediments defined as not suitable for re-immersion in the sea, can be treated with reclamation techniques, usually used in the second strategic approach, to reclassify the quality of the sediments, making them suitable for a new immersion and for beach nourishment.

This process requires the definition of three key aspects:

- 1) in situ, pre and post treatment characterization
- 2) distribution and handling of pollutants during dredging and re-immersion operations
- 3) suitable treatment techniques, also in the supply chain, for the treatment of the specific contamination (physical-chemical and biological train treatment).

During this management process, people must decide whether (or not) to treat the sediments, whether to store them on land to be treated and/or recovered or whether to put them back into the sea, whether to mitigate the risk within situ treatment and recovery interventions or off-situ, biological, chemical, physical or in the supply chain and so on.

With this mission, researchers from the universities of Enna, Genoa, and Palermo (**UKE, UniGe and UniPa**) developed synergistic work aimed at the analytical evaluation of the effects of the movement and treatment chain of dredged marine sediments. The activities include the application of studies based on mathematical models (for the study of the impacts and effects of the "fate and transport" process), physical models referring to applications in bench scale or pilot plants (for validating the results and the model calibration), modeling to simulate and support monitoring in the coastal environment, *ante-* and *post operam*, all with the help of "sea truth" activities. The synergistic work was also based on the results obtained in transversal tasks where UKE (together with the aforementioned partners) has developed specific activities on sediments: **Task 4.5.1**, relating to the chemical-physical treatment of contaminated marine sediments; **Task 4.5.2**, relating to the biological treatment of contaminated sediments.

In this context, **Task 4.5.3** defines and completes the knowledge on the treatment and rational management of treated sediments (according to the objective of minimum environmental and social risk): the investigation of new processes has been completed (such as desorption thermal) and an analysis of the processes was proposed according to a preliminary and general model of risk assessments, opportunities and repercussions (SWOT analysis and consequent FMEA). Particularly: SWOT, precisely, stands for *Strengths (strengths)*, *Weaknesses (points of weakness)*, *Opportunities (opportunities)* and *Threats (threats)*; on the other hand, the FMEA is the *Failure Mode and Effects Analysis*.

Some specific activities concerned: development of the method to support decisions by means of assessments based on "fate and transport" models integrated with the modeling of "in-chain" treatment processes (**UKE**); applications of in-situ mitigation methods, based among others, on mycoremediation for the mitigation of the diffusion of heavy metals during dredging and re-immersion operations (**UniGe**); evaluation and studies on off-site treatments for the decontamination and recovery of contaminants, comparing the results of different processes or applications in the supply chain, based on both biological (bioslurry) and physical-chemical (thermal desorption) processes (**UniPa**).

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## FIRST SECTION: TASK GOALS

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### INTRODUCTION

**Task 4.5.3** aims to develop quantitative methodologies for multi-risk assessments to identify effective and economically sustainable strategies to mitigate the impacts associated with sediment management in marine coastal areas and in ports affected by dredging or remediation operations.

Sediments are essential components of all aquatic systems and are subject to high anthropogenic inputs, representing a potential reservoir of toxic compounds. In the last decades, coastal ecosystems have drastically changed due to human activities, which caused severe ecological impacts. In the marine environment, they constitute an extremely complex environmental compartment. In fact, they can represent a vast range of sources of risk, and the possible interactions can cause different scenarios with cascading effects. Their management is a complex process that involves different phases, among which the characterization, the transport, the treatment, and the destination of the materials.

The task proposes a decision support system to identify optimal management strategies. The decision support system incorporates regulatory frameworks and scientific methodologies in order to evaluate and mitigate the impacts associated with the movement and the treatment guaranteeing the environmental, economic, and social sustainability.

The first phase of the task involved the characterization of the sediments, which includes the analysis of the samples to determine the nature and the extension of the contamination.

Currently, the regulatory guidelines are based on two different strategic approaches.

The first approach is based on the results of the ecological analysis based on the qualitative classification of the sediments, an analysis that characterizes them from the Eco-toxicological and chemical point of view. With this approach, sediments of good quality can be reused and therefore re-immersed in the sea, while in the opposite case they must follow different management paths, starting from the storage in the containment basin up to their possible disposal in a special landfill.

The second strategy refers to explicitly contaminated areas and is based on environmental risk analysis. With such an approach, the contaminated sediments must be remediated in order to be recovered by bringing the environmental contamination below the so-called risk threshold.

In both cases, fate and transport models are essential in order to evaluate the environmental and health impacts. On the other hand, it is important to define the best practice for treatment of contaminated sediment.

The task also integrated risk analysis tools, such as SWOT and FMEA, in order to identify and classify the risks associated with sediment management and the use of adequate treatment techniques, targeted at specific contaminations, guaranteeing sustainable solutions **across** the supply chain.

In summary, during this management process, it is necessary to decide whether or not to treat the sediments, whether to store them on land to be treated and/or recovered, whether to re-immerses them in the sea, whether to mitigate the risk through treatment and recovery interventions in situ or off-site, biological, chemical, physical, or along the supply chain, and so on.

To reach these objectives, the work integrated advanced tools and techniques, among which:

- bench-scale and pilot-scale applications, fundamental for the validation of the results and the calibration of the models.
- mathematical models, used in order to simulate the processes (or "fate and transport" phenomena) and predict the environmental impacts;
- simulations and environmental monitoring, in order to evaluate the effects of the operations before and after their execution.
- field verification activities, necessary in order to integrate the model data with real observations.

Through this work, **task 4.5.3** tries to provide practical and sustainable solutions for the management of marine sediments, guaranteeing the protection of the marine environment.

## AIM AND GENERAL EVALUATION

### MARINE SEDIMENT REGULATION

The Italian and European regulations on marine sediments have evolved over time, progressively defining in detail the definitions and criteria for the proper management of this environmental matrix.

One of the first regulations, Italian Ministerial Decree (D.M.) 24/01/1996, governed the discharge into the sea of materials derived from the excavation of marine or brackish seabed, as well as from other sediment movements in the marine environment.

The following year, through Italian Legislative Decree (D.Lgs) 22/1997 (Decreto Ronchi), the European Waste Catalogue (CER) was introduced in Italy, classifying dredged sediments as potential waste and thus imposing management and traceability obligations. D.M. 5/02/1998 identifies non-hazardous waste subject to simplified recovery procedures.

Sediments are included among the types of waste eligible for these procedures and regulated by Annex 1, Sub-Annex 1, provided they meet specific criteria and technical regulations.

- The D.Lgs. 152/2006, Environmental Consolidated Act, allows sediments to be excluded from waste regulations.
- The Article 185, paragraph 3, excludes sediments if moved within surface waters or within hydraulic properties for water and river management, flood prevention, flood or drought mitigation, or soil restoration, provided it is proven that the sediments are non-hazardous according to Decision 2000/532/EC of the Commission of May 3, 2000, and subsequent amendments.
- The Article 109 regulates the immersion in the sea of dredged materials from marine or brackish seabeds, providing for specific authorizations for activities such as beach nourishment or sediment re-immersion.

Law 116/2014 introduced Article 184-quater into the Environmental Code, regulating the cessation of waste classification for dredged materials subjected to specific recovery operations and compliant with contamination limits.

Dredged materials cease to be waste if, after recovery operations, which may also include sorting and selection, they do not exceed the contamination threshold concentrations set in Columns A and B of Table 1, Annex 5, Title V, Part Four, and if the destination site is certain and they are directly used, including for reuse or environmental reshaping, without risks for the affected environmental matrices, particularly ensuring no contamination of groundwater and surface waters.

In case of direct use in a production cycle, they must comply with the technical requirements for specific purposes, the applicable regulations and standards for products and raw materials, and must not generate emissions into the environment that exceed or differ qualitatively from those resulting from the use of authorized products and raw materials.

For port areas, Law 84/1994 (Article 5-bis) regulates dredging within Sites of National Interest (S.I.N.) and marine-coastal areas.

In S.I.N., if sediments meet contamination limits, they can be reintroduced into the water body or used for coastal nourishment; otherwise, remediation is required. In alternative, they can be placed in containment basins if compatible with environmental and health protection.

D.M. 161/2012 had included sediments among excavated soils and rocks (TRS), treating them as by-products under Article 184-bis, but the Decree of the President of the Republic (D.P.R.) 120/2017 revoked this classification, excluding them from the benefits provided for TRS.

In 2016, the MATTM (Italian Ministry for the Environment, Land, and Sea Protection) issued three decrees to regulate the sector:

- Decree of the Director General (D.D.) 351/2016, which defines pollutant limits for excluding marine areas from S.I.N. classification;
- D.M. 172/2016, which regulates dredging in port and coastal areas;

- D.M. 173/2016, which establishes technical criteria for the immersion and management of non-S.I.N. sediments.

These decrees are supplemented by technical documents available on the Italian Institute for Environmental Protection and Research (ISPRA) website (<https://www.isprambiente.gov.it/files/software/decreto-15-luglio-2016-n173>), and the MATTM Circular 469/2019, which clarifies the application of D.M.173/2016 and Article 109 of D.Lgs.152/2006.

At the European level, the Water Framework Directive (2000/60/EC) and the Marine Strategy Framework Directive (2008/56/EC) require an ecologically sustainable management of sediments.

Dredging operations must ensure the maintenance of ecological status in water bodies and may require Environmental Impact Assessment (EIA), Integrated Environmental Authorization (AIA), or Appropriate Assessment (VInCA - Environmental Impact Assessment) in sensitive or protected areas.

The regulatory framework offers various sediment management scenarios: they can be treated as waste, as by-products (if not initially classified as waste), as end-of-waste materials, or excluded from waste regulations if reintroduced into the same water body without environmental risk. The classification depends on the degree of contamination, the area of intervention (S.I.N. or not), and the purpose of sediment movement (maintenance or remediation).

### CONCEPTUAL MODEL AND FLOWCHARTS OF TASK APPROACH

As regards the management of marine sediments, the possible management choices involve a very wide range of possibilities: certainly, the definition of "contaminated", "non-contaminated" or "potentially contaminated" sediment can strongly influence "the direction of the choices". The sedimentary matrix dredged, from small or large ports, or from the coastal area in general, tends to be recovered where it is not contaminated. The most obvious and environmentally shared solution is to re-introduce (into the sea) the sediment into suitable areas or use it (depending on the grain size of the sample) as beach nourishment. On the contrary, if the sediment is of poor quality, and with a more or less "severe" level of contamination, the sediment must be appropriately stored or treated before any subsequent recovery or reuse.

In this context, the socio-economic reality of the territory and the real condition of the services and intended use in the geographical area concerned can play a key role in management choices, which may differ from region to region, despite the starting technical-practical affinity. Here the decision tree can branch significantly in different directions, leading to a series of different solutions that are not easily interpretable.

**Figure 1.1** represents a scheme of possible choices that the manager should evaluate for the correct management of this environmental matrix, one of the most complicated and debated in the environmental field: dredged marine sediments. In this context, simple analysis tools of opportunities and risks could help the management and fate of matrices as they are or "reclaimed".

The Aim of **Task 4.5.3** of RETURN project concern the development of quantitative and probabilistic methodologies for multi-risk assessments. This is important in order:

- 1) to support the identification of effective and economically sustainable strategies;
- 2) for the mitigation of the impacts due to the handling of sediments in coastal marine areas and harbors, affected by maintenance or reclamation dredging operations.

In this scenario, multi-risk analysis would make it possible to develop useful decision support aimed at defining the best management scenario.

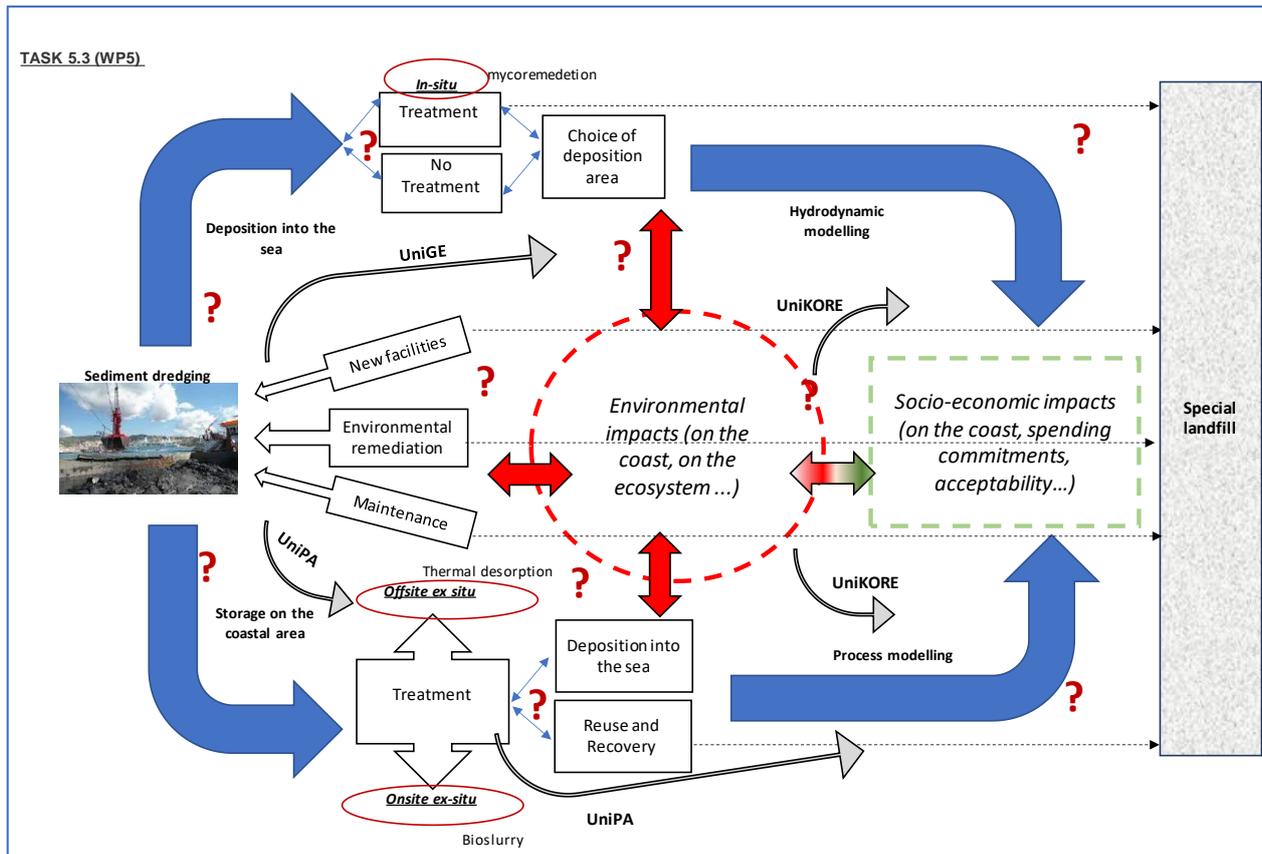


Figure 1.1- Conceptual flow chart on the choices to be faced in the management of dredged sediments

More in detail, the research units of **Task 4.5.3** developed a synergistic work aimed at the analytical evaluation of effects of the movement and treatment of dredged sediments. The analytical approach combines and integrates specific experimental methods (for the preliminary study of the impacts and effects of the "fate and transport" process), analysis of physical models referred to applications in bench scale or pilot plants (for the validation of the results and model calibration), subsequent mathematical simulations for the support of monitoring in the coastal environment, ante and *post-operam*, and data acquisition for what is called 'sea truth'.

First, it must be underlined that the management of contaminating marine sediments is very costly, both in economic and environmental terms. The interdisciplinary nature of topics and regulations brings the manager of these matrices to numerous crossroads of choice, which, depending on the territory and the socio-economic balances involved, can lead to different approaches and processes (treatment, re-immersion, reuse etc).

The topic of multi-risk analysis applied to such a complex system of processes, such as the movement of more or less contaminated marine sediments, risks being difficult to manage a priori: there are in fact many aspects that need to be considered.

- General aspects: mainly linked to the origin of the sediments and the reason for their movement.
- Regulatory aspects: linked to the origin of the activities and any evidence of contamination in the areas to be dredged
- Technical aspects: linked to dredging methodologies (environmental or not) and the operational use of the ports involved in handling activities.
- Application aspects: linked to the need or otherwise to treat the sediment before its subsequent destination (whether re-introduction or reuse).
- Aspects of real applicability of intervention: aimed both at remediation technologies and at the territorial presence of the end user or residual disposal.
- Economic aspects: linked to all the implications and cost-benefit evaluations of each single previous aspect.

Based on this simple introduction, which among other things includes only a part of the possible arguments of interest, the extreme complexity of guaranteeing a complete approach right from the start is highlighted. For this reason, the analysis of choices, or therefore the evaluation of possible risks and effects, cannot ignore planning that involves a systematic approach:

1. preliminary analysis of strengths and weaknesses, according to a semi-qualitative analysis approach,
2. identification of the list of INPUT information necessary for the analysis;
3. in-depth analysis of the aspects with a semi-quantitative Risk Analysis (AdR) approach;
4. Output information;
5. List of priorities for choosing and mitigating process "failures/breakdowns".

In particular, the first 3 points of the previous analysis framework could require an iterative approach: where new evidence of probable effect (risk) and/or consequential damage were to emerge from the basic analysis, the information enrichment process could undergo a further "extension of concepts" that could enrich the decision-making tool

In this sense, therefore, the risk analysis identified, as happens with the ordinary risk analysis approach of the dynamic production process, should be continuously updated on the basis of the aspects previously identified and which accrue (over time) an enrichment of information both site-specific (regions, municipalities, territories of real applications, beyond the proof on concept) and of future regulatory direction (regulatory modifications and additions probabilistically developed in phases following the revision of the AdR).

With reference to the above list, [Figure 1.2](#) shows the scheme of the activities proposed within **Task 4.5.3**, which provides for the close correlation between activities developed specifically within the same task and the evaluations/data coming from the Parallel experimental and research approaches developed in other tasks of WP5 (also extending to other WPs in the future), such as **tasks 4.5.1** and **4.5.2**.

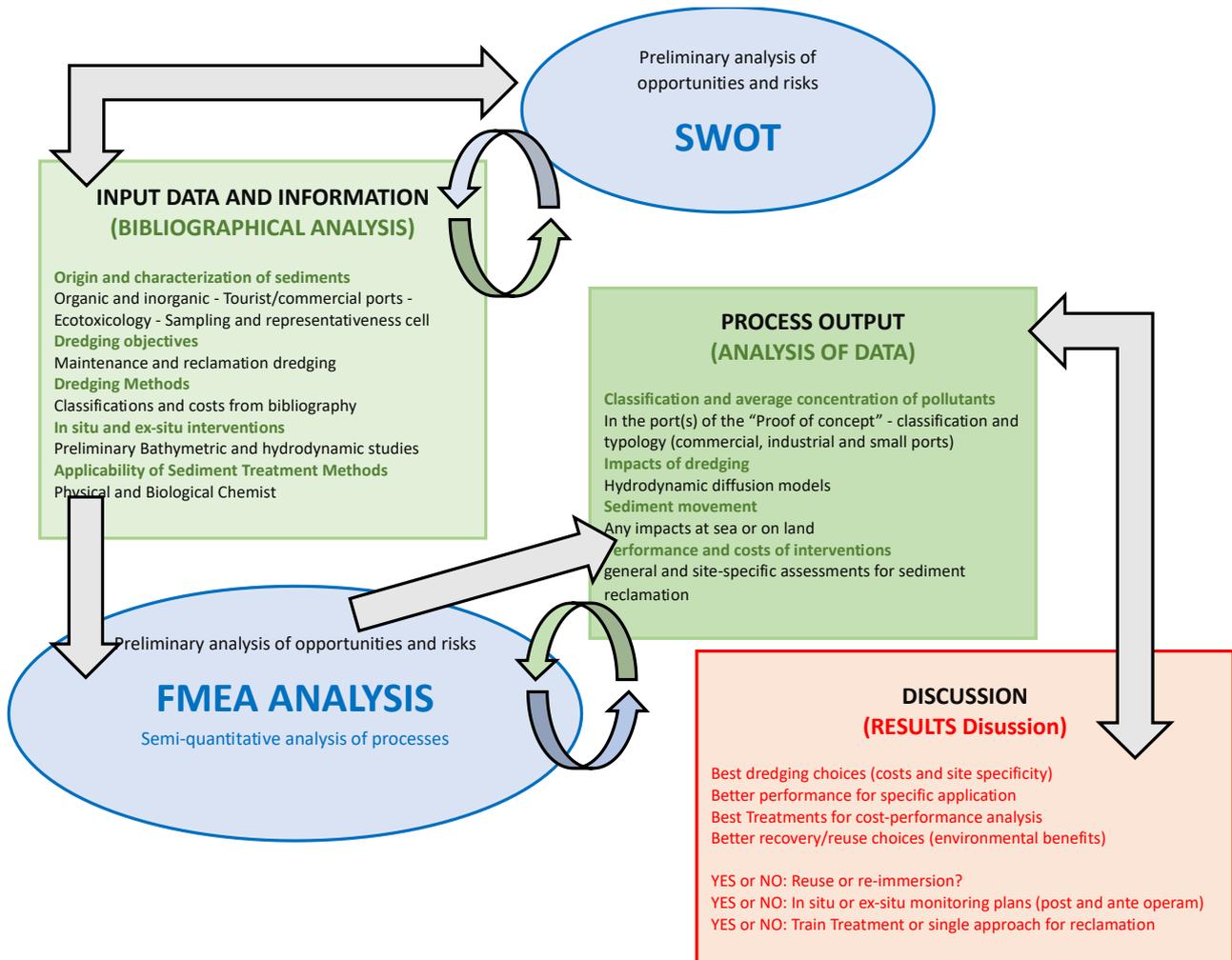


Figure 1.2 - Scheme of the activities proposed within Task 4.5.3

As shown in Figure 1.2, in order to identify the preliminary actions and preliminary aspects on which to focus attention, a "general" risk analysis was proposed that allows the identification of strengths and weaknesses based on predominantly qualitative considerations but specific to the intervention scenario.

In particular, S.W.O.T. analysis allows identification of the strengths, weaknesses, opportunities and threats of a specific project or action plan. It is a tool that can help the work team plan strategically. SWOT, precisely, stands for Strengths (strengths), Weaknesses (points of weakness), Opportunities (opportunities) and Threats (threats).

Although it is widely used by many organizations, from small businesses to non-profits to large enterprises, the SWOT analysis can be used for many personal and professional purposes, as it is a powerful tool that helps identify competitive opportunities for improvement. This way, you can improve your decision-making process by restating any risks of failure.

Simply put, each of these factors must be carefully examined to adequately plan for planning growth. This is where analytics comes in.

The first "return" of the SWOT analysis is certainly to highlight the most sensitive aspects that can affect the optimization of the decision-making process. In the case of application to the topic addressed in task 4.5.3., the SWOT analysis suggests the INPUT DATA and PROCESSES on which to focus the subsequent analysis and in-depth analysis. The specific aspects of intervention include the following (deduced from a first "run" of application of the SWOT analysis).

- Origin and Characterization sediments - revalent organic or inorganic pollution; - Tourist or commercial ports analyzed; influence of Ecotoxicology aspects; the representativeness of the sampling (for representativeness cells); etc.
- Objectives of dredging – maintenance (contamination is probable but not clear-cut) or remediation (full-blown contamination).
- Dredging methods: closely linked to the previous point, there is a difference in the approach of environmental or ordinary dredging and in this sense; the choice should be made not only on the basis of operating costs but also on the real risk of impact during operations of movement.
- In situ or ex situ interventions: The initial choice depends on whether you intervene with treatment or safety measures. In the case of in-situ interventions, further evaluation aspects emerge based on the hydrodynamic and bathymetric conditions of the seabed. In-situ interventions, however, should be oriented towards the recovery of the resource, "leaving the uncontaminated matrices to the sea" in order to reduce environmental depletion.
- Applicability of treatment methods: the treatment of contaminated marine sediments starts from technologies and techniques applied to soils, as many of these are effective for the sediments. Furthermore, depending on the pollution, which is the most suitable process: chemical, physical and biological. Although task 4.5.3 was initially focused on biological aspects, it must be considered that in the case of sediments a "train treatment" process is often effective for the complete removal of pollutants or, alternatively, to prepare the matrix for biological degradation of the bacteria in the presence of multipollutant.

The list of input data defined by the preliminary analysis, which can be extended based on subsequent reviews and interactions, requires the specific study of each single aspect that, as a domain effect, involves assessments and knowledge, which are in turn different. In this sense, the FMEA analysis is an AdR tool quantitatively aimed at defining the priority aspects of risk mitigation.

## SWOT AND FMEA ANALYSIS

The definition of risk and Risk-Based Thinking have become predominant in quality systems with the latest version of the ISO 9001 standard. These concepts are indeed explicitly stated in the standard, but they were already present "between the lines" in the 2008 version.

The ISO 31000 standard defines risk as an effect of uncertainty on objectives. It is easily deduced from this definition how this can generate both a positive event and a negative event, despite the fact that, in everyday usage, we tend to associate risk with a purely negative event.

Risk analysis consists, first of all, in the identification of the risk and its nature, but also in the analysis of its causes and potential consequences. Only with an understanding of these factors will it be possible to make choices to adequately address them.

In **Task 4.5.3**, SWOT and FMEA risk analyzes were used. The first one aims at a strategic analysis to make decisions with a purely qualitative method, while FMEA has a semi-quantitative approach.

The SWOT analysis tool, also known as SWOT matrix, allows evaluating both the positive and negative aspects of the internal and external context.

SWOT (Strengths, Weaknesses, Opportunities and Threats): where the first two elements refer to the internal context and are specific to the organization, while the last two refer to the external context, including all the factors that do not belong to the organization itself but rather to everything that surrounds it.

- Strengths (S) – These are the aspects considered strong points of the organization, where it excels.
- Weaknesses (W) – Unlike strengths, these are the areas where the organization is lacking or at least not sufficiently prepared.
- Opportunities (O) – These are opportunities arising from everything that surrounds the organization. Useful factors may include geographical location, the presence of key stakeholders in the area, legislative decrees, etc.
- External Threats (T) – The same factors that may present opportunities can automatically become threats for organizations that are not adequately prepared.

The SWOT analysis should help in understanding the factors surrounding the organization and placing them in the appropriate position. The next effort should be to transform weaknesses into strengths and threats into opportunities.

We can easily observe how risks can (and should) also be placed within the SWOT matrix, categorized into internal and external context. At this stage, identifying and assessing risks is an almost mandatory step to making the SWOT analysis effective. Transforming risks into opportunities to seize or into strengths thus becomes the new mission, aligning perfectly with the latest version of ISO 9001.

The FMEA (*Failure Mode and Effects Analysis*) was chosen for use within **task 4.5.3** because it is a multidisciplinary quantitative analysis developed by a team of experts who are involved in order to identify potential causes of error, quantify severity, and assess preventive actions to be taken to avoid their occurrence (general scheme in [Figure 1.3](#)).

This type of analysis is used during the design phase to mitigate the occurrence of issues that could compromise the entire process.

Failure modes are analyzed through an effects analysis, identifying potential causes of error, how they can be detected, and the frequency with which they may occur.

Once the risks have been quantified, corrective actions to be taken are suggested, and the responsible individuals for the intervention are defined.

In the context of the RETURN Project, the FMEA analysis can be applied in different phases of the sediment dredging and remediation process:

- Planning
- Dredging
- Transport and temporary storage
- Remediation treatment
- Outcome verification
- Reuse or disposal.

The SWOT analysis was presented only after collecting input data (related to characterization, treatment, operational feasibility, etc.), in order to organize and standardize the available information.

On the other hand, the FMEA has been presented as a mere analysis tool: the procedure and completion of the FMEA approach is complicated and dynamic, in continuous and perpetual updating. In this case, following the SWOT analysis, examples of potential failures have been identified and analysed across various development phases (dredging, in-situ treatment, ex-situ treatment, reuse, etc.)

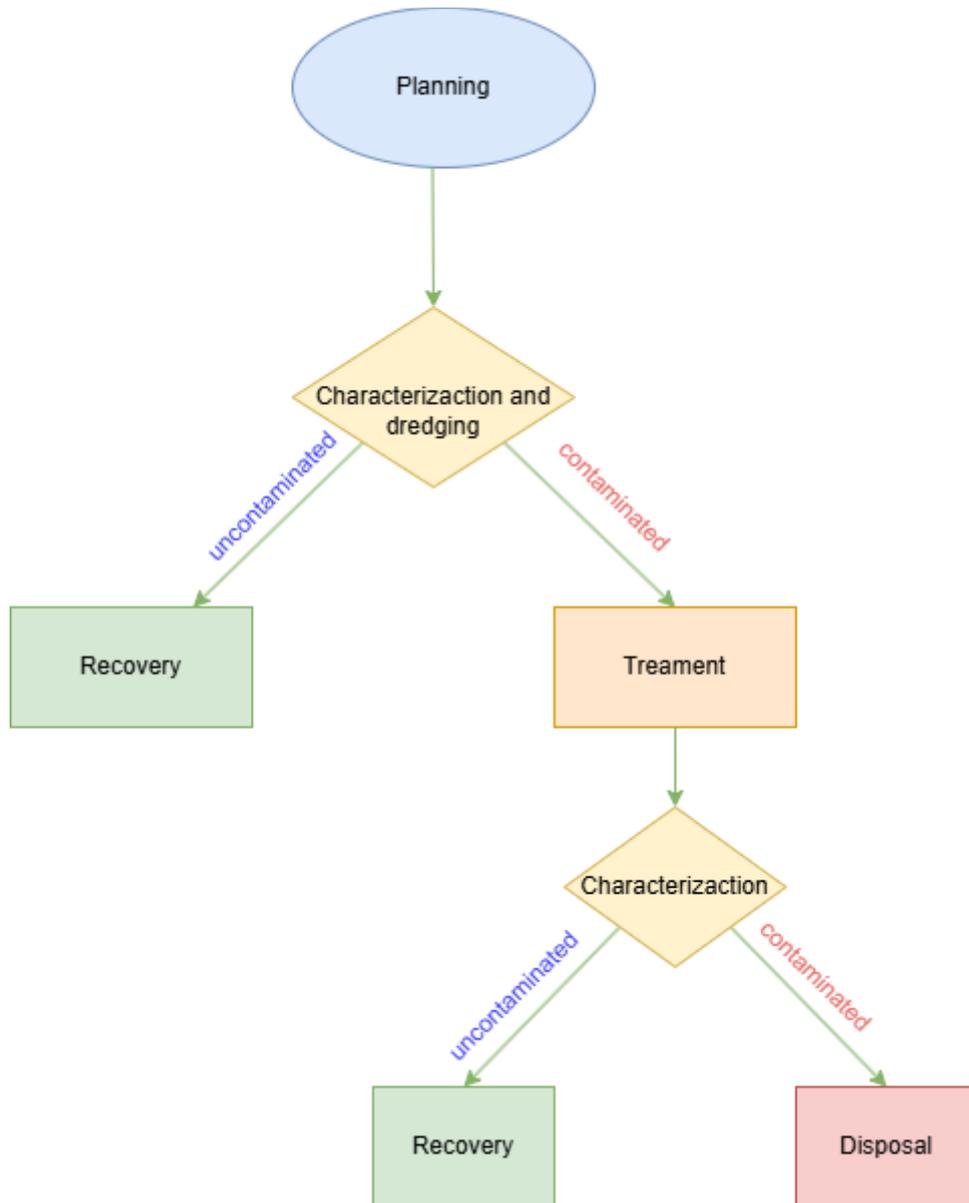


Figure 1.3 - Scheme of the FMEA analysis

## SECOND SECTION: GENERAL BIBLIOGRAPHICAL ASPECTS

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### SAMPLING CRITERIA FOR SEDIMENTS TO BE SUBJECTED TO MOVEMENT.

The assessment of sediment quality is not easy to define, as sediments are complex systems and their interaction with the ecosystem is equally complex. There is no universally accepted methodology for assessing the state of pollution of sediments. The determination of pollution is influenced by the difficulty of obtaining information from the system without disturbing it and interpreting it, furthermore sediments are composed of many microenvironments, in which chemical, physical and biological conditions can vary and these in turn influence the environmental toxicity of the contaminants contained in the sediment and their bioavailability but the objective of guaranteeing the quality of sediments is also necessary to ensure the protection of water quality and the validity of the results obtained in the characterization phase of the site that hosts these materials. The main objectives of the characterization in terms of sediment quality are closely linked to the proper performance of the studies of an area to be reclaimed and are ideally divided into two phases:

- Priority phase;
- Detail phase.

The Priority phase (1<sup>st</sup> phase) is characterized by operations aimed at evaluating the horizontal and vertical distribution of contaminants, and the possible correlations between contaminant distribution and granulometric characteristics of the sediments. Furthermore, it is a priority to establish the effects of contamination on living organisms, the bioavailability of the pollutants identified and the possible transfer to food networks, in particular cases and in particularly sensitive areas the concentration of contaminants along the water column, and the contribution of heavy metals, distinguishing between natural and anthropogenic sources.

In the Detailed (second) Phase the study is completed by examining the chemical, physical and ecotoxicological characteristics of areas possibly not investigated in the first phase, analytical investigations can be carried out on the samples taken previously, investigations on the water column, on benthic and necto-benthic populations (ISPRA, 2012) The first thing to do is therefore to study the horizontal and vertical distribution of contaminants within the sediments.

The optimal sampling strategy must allow a significant characterization of the entire surface and volume of material to be moved. The sampling criterion described takes into account the bathymetric heterogeneity of the seabed, the qualitative variability of the sediments, as well as the internal structural articulation of Italian ports. It provides for three types of unit areas (APAT-ICRAM, 2007), each of which must be characterized by a single sampling point and positioned close to the internal structures of the port (type 1), in the central areas of the port at a distance from the structures (type 2) and in the areas at the entrance of the ports or along the coastlines adjacent to port areas (type 3), provided that there is no specific contamination deducible from previous information.

#### ➤ Type 1 (Ports)

Along the internal perimeter characterized by the presence of structures, such as jetties, docks and docks, a 50 m x 50 m square mesh grid must be superimposed on the area to be dredged (unit sampling areas of type "1"). Any residual areas, resulting from the subdivision into lots of 2,500 m<sup>2</sup>, can be omitted if their surface area is less than 1,500 m<sup>2</sup>.

#### ➤ Type 2 (Ports)

In internal areas at distances greater than 50 m from the structures, a square mesh grid with a side of 100 m must be superimposed on the area to be dredged (unitary area of type "2"). This grid of unitary areas must be positioned in contiguity with any unitary areas of type "1" and "3". Any residual areas resulting from the subdivision into lots of 10,000 m<sup>2</sup> may be omitted if their surface area is less than 5,000 m<sup>2</sup>.

➤ **Type 3 (Ports and adjacent areas)**

Within the port entrances, the external areas adjacent to the port, along the external protection dams and breakwaters, as well as other areas adjacent to the coastline, a grid with a square mesh of 200 m side (unit area of type «3») must be superimposed on the area to be dredged. This grid of unit areas must be positioned adjacent to the grids of unit areas «1» and «2» where present. Any residual areas resulting from the division into lots of 40,000 m<sup>2</sup> may be ignored if their surface area is less than 10,000 m<sup>2</sup>. In each unit area, regardless of the type, at least one sampling point must be identified, representative of the area, and positioned according to the volume of material to be dredged and the distance from the point of the adjacent unit areas.

Regardless of the surface area involved, the number of points must not be less than 3. The height of each individual core taken must be at least equal to the thickness of the material to be removed expected at the sampling point.

Below are schematically reported some graphic examples of the sampling grids described in the previous cases (Figure 2.1- 2.2).

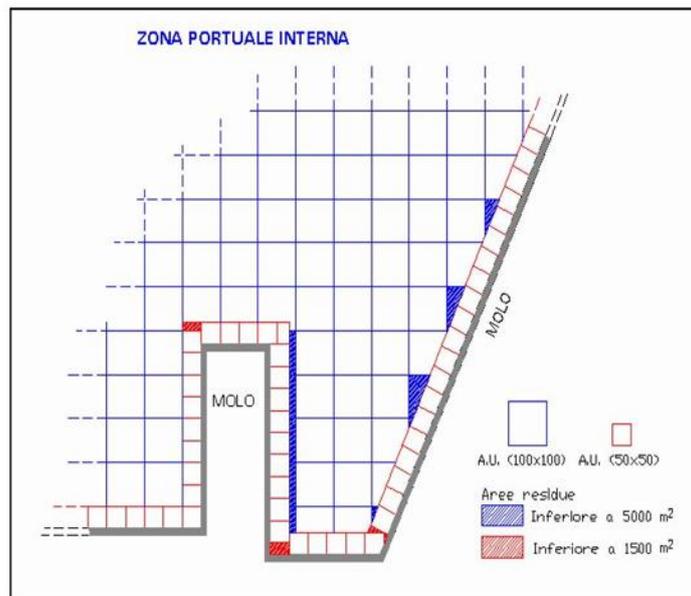


Figure 2.1 - Example of Sampling in the internal port area (Figure with Italian references referring to APAT-ICRAM (2007), Italian legislative reference regulation)

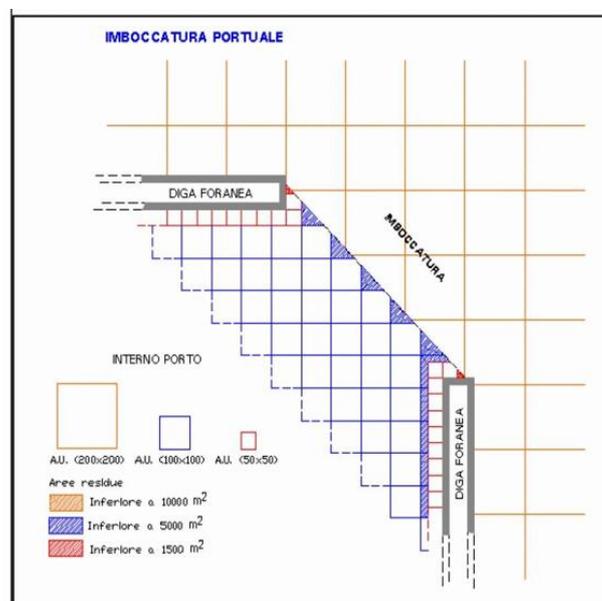


Figure 2.1 - Example of Sampling of the port entrance (Figure with Italian references referring to APAT-ICRAM (2007), Italian legislative reference regulation)

Sections of approximately 50 cm must be taken from each core, according to the following indications (APAT-ICRAM, 2007).

- Cores up to 2 m high must be divided into sections of 50 cm, starting from the top, taking a number of sections from 1 to 4, depending on the length of the core, leaving out the deepest section when the latter is less than 25 cm.
- For cores with a height greater than 2 m, in addition to the 4 levels referred to in the previous point, a section of 50 cm must be taken representing each subsequent interval of 2 m, leaving out the section relating to the deepest interval when the latter is less than 1 m;
- If it is ascertained that the natural geological substratum constituting the area has been reached, appropriately documented in the technical report, for which any anthropogenic contamination can be excluded, it is sufficient to take a single section of length 50 cm representing the entire base layer.

Below 5 different examples are reported for typical core characterization (Figure 2.3-2.6).

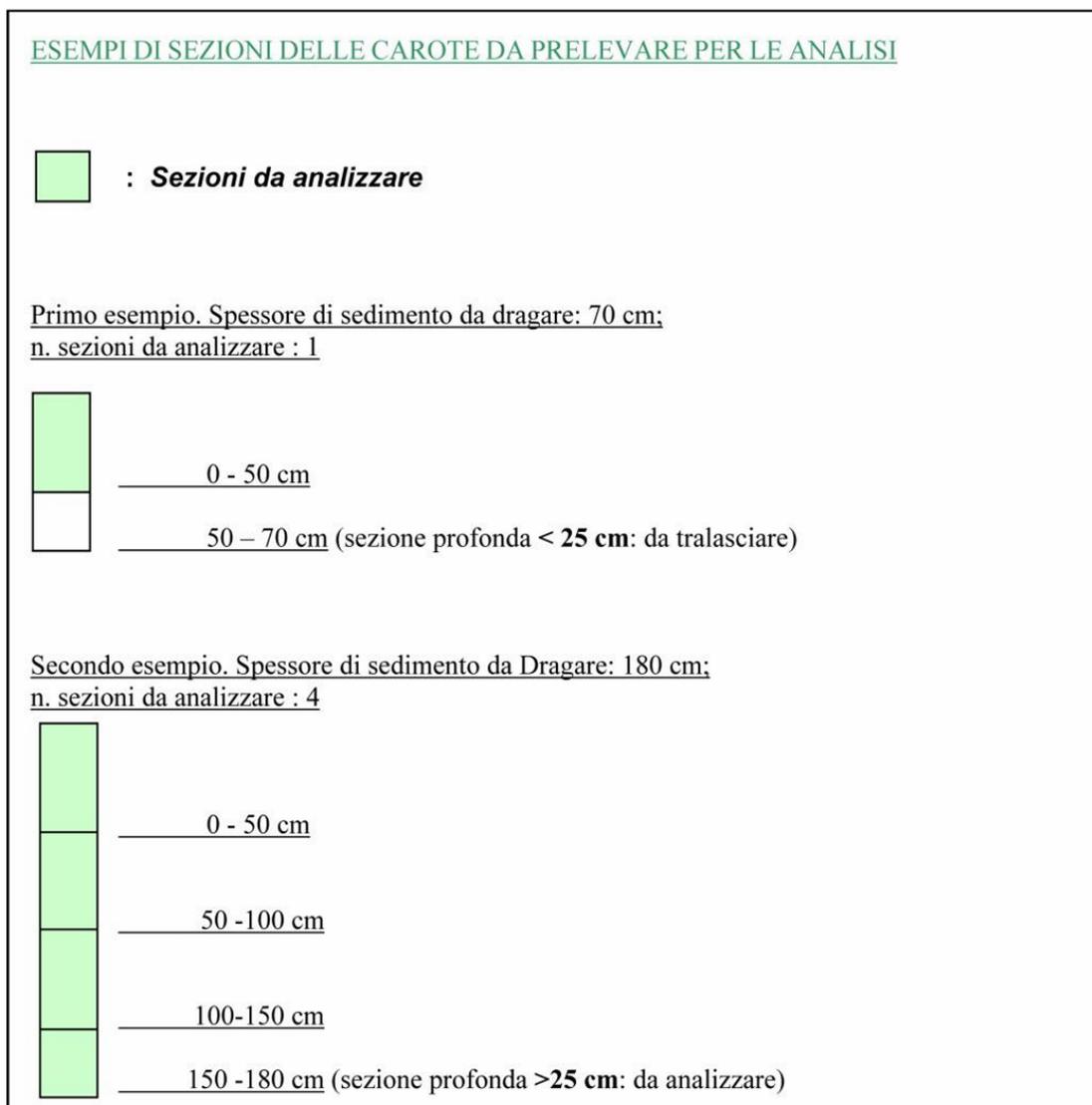


Figure 2.2- Section of the cores to be collected for analysis, example 1 and 2 (Figure with Italian references referring to APAT-ICRAM (2007), Italian legislative reference regulation)

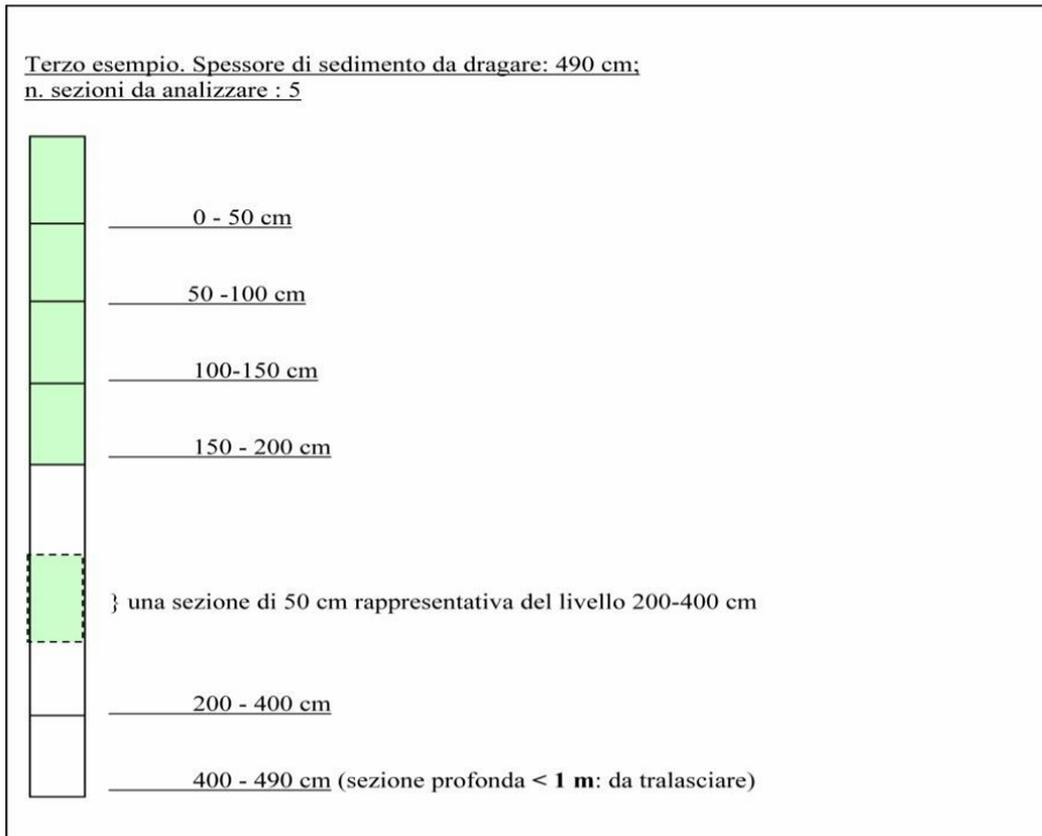


Figure 2.3 - Section of the cores to be collected for analysis example 3 (Figure with Italian references referring to APAT-ICRAM (2007), Italian legislative reference regulation)

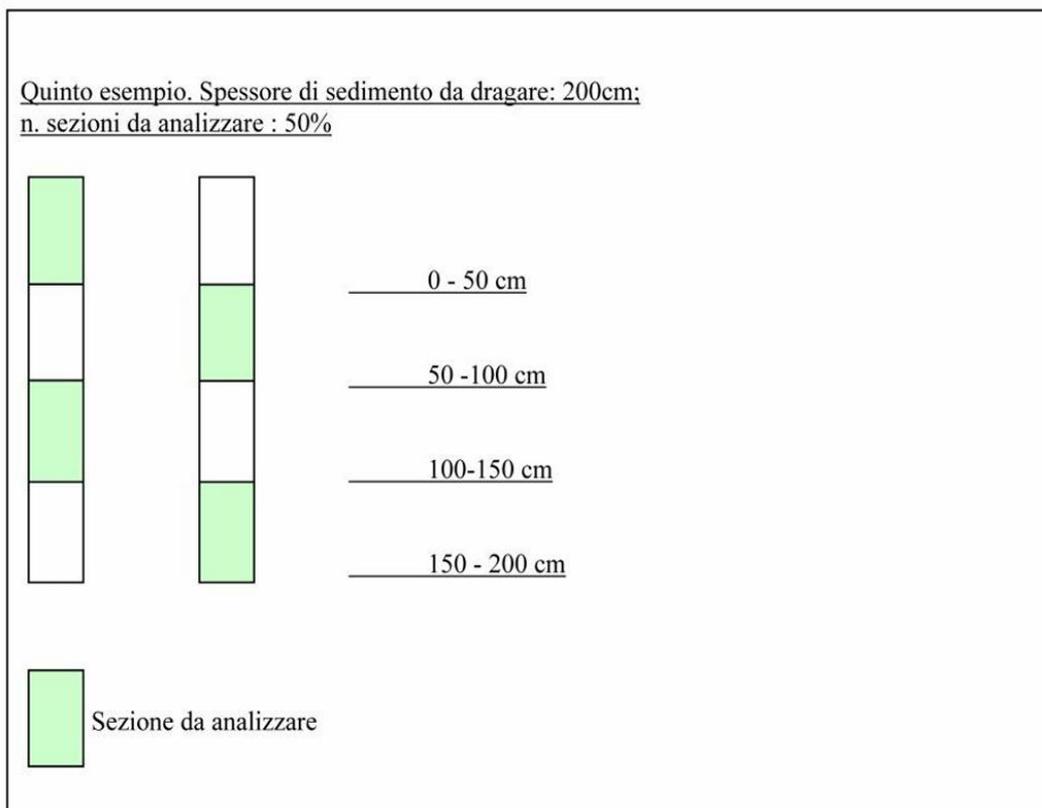
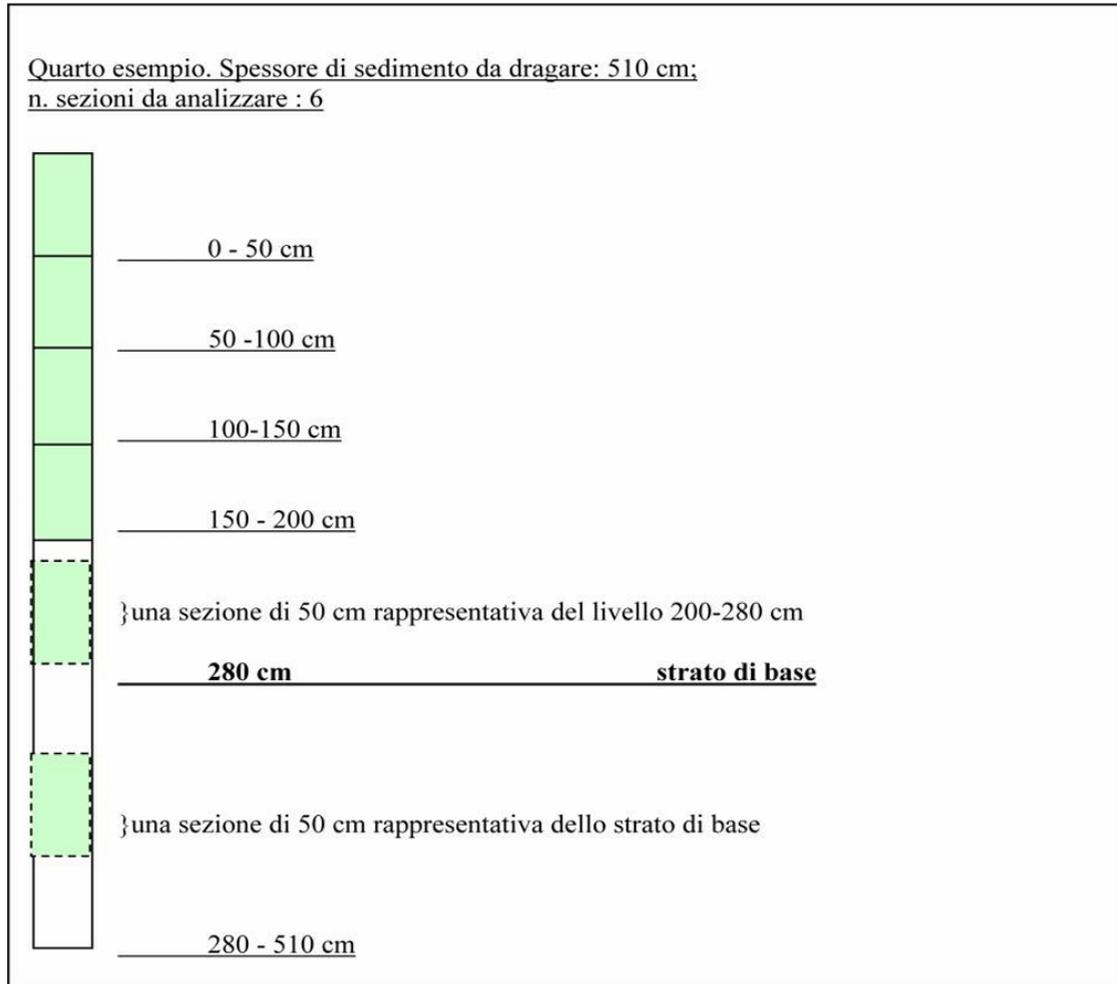


Figure 2.4 - Section of the cores to be collected for analysis, example 4 (Figure with Italian references referring to APAT-ICRAM (2007), Italian legislative reference regulation)



**Figure 2.5-** Sections of the cores to be collected for analysis, example 5 (Figure with Italian references referring to [APAT-ICRAM \(2007\)](#), Italian legislative reference regulation)

### CHEMICAL-PHYSICAL ANALYSIS OF SAMPLES

Once the samples have been collected, it is possible to proceed with the analysis. The list of parameters to be analysed varies according to the sampling area and the intended type of analysis. For the chemical, physical and microbiological ones, the parameters to be analyzed are included in the tables below in relation to the collection site ([APAT-ICRAM, 2007](#)): [Table 2.1](#).

Analyses must be carried out to search for substances whose presence cannot be excluded on the basis of previous investigations, as well as on the basis of the list of priority substances referred to in the decision of the European Parliament no. 2455/2001/EC.

Analyses concerning additional substances must be carried out on a representative number of samples, chosen to obtain the most representative distribution possible of the area to be characterized, with particular attention to the areas with presumed greatest contamination.

Table 2.1 - Chemical-physical analyses relating to port areas (extract from Table 2.1a of APAT-ICRAM, 2007)

	PARAMETRO	SPECIFICHE
ANALISI FISICHE	Descrizione macroscopica	Colore, odore, presenza di concrezioni, residui di origine naturale o antropica
	Granulometria	Frazioni granulometriche al $1/2\phi$ dove $\phi = -\log_2$ (diametro in mm/diametro unitario in mm)
	Mineralogia (2)	Principali caratteristiche mineralogiche
ANALISI CHIMICHE	Composti organostannici(1)	Sommatoria: Monobutil, Dibutil e Tributilstagno
	Metalli	Al, As, Cd, Cr totale, Pb, Hg, Ni, Cu, V, Zn
	Idrocarburi Policiclici Aromatici (IPA)	IPA totali: [Fluorantene, Naftalene, Antracene, Benzo(a)pirene, Benzo(b)fluorantene, Benzo(k)fluorantene, Benzo(g,h,i)perilene, Indopirene, Acenaftene, Fluorene, Fenantrene, Pirene, Benzo(a)antracene, Crisene, Dibenzo(a,h)antracene, Indeno(1,2,3,c-d)pirene]
	Idrocarburi Totali	Possibilmente distinti in $C < 12$ e $C > 12$
	Pesticidi Organoclorurati	Aldrin, Dieldrin, $\alpha$ -esaclorocicloesano, $\beta$ -esaclorocicloesano, $\gamma$ -esaclorocicloesano (Lindano), DDD, DDT, DDE (per ogni sostanza: somma degli isomeri 2,4 e 4,4), HCB, eptacloro, eptacloro epossido, ossiclordano, cis-clordano, trans-clordano, trans-nonacloro, cis-nonacloro, eldrin, mirex, metossicloro
	Policlorobifenili	Congeneri: PCB 28, PCB 52, PCB 77, PCB 81, PCB 101, PCB 118, PCB 126, PCB 128, PCB 138, PCB 153, PCB 156, PCB 169, PCB 180 e loro sommatoria
	Clorobenzeni	Esaclorobenzene
	Carbonio organico totale o sostanza organica totale	
	Azoto Totale	
	Fosforo Totale	
ANALISI MICROBIOLOGICHE	Coliformi	<i>Escherichia coli</i>
	Enterococchi	Fecali
	Salmonelle	
	Clostridi	Spore di clostridi solfito-riduttori
	Stafilococchi	
	Miceti (2)	

(1) Parametro da ricercare su 1/3 dei campioni, scelti in modo tale da avere una distribuzione omogenea rispetto al volume di materiale da caratterizzare.

(2) Parametro da ricercare su almeno 3 campioni, scelti in modo tale da avere una distribuzione omogenea rispetto al volume di materiale da caratterizzare, nel caso di sedimenti di cui si chiede l'utilizzo per ripascimenti. Il numero dei campioni da considerare deve essere superiore in casi di elevata eterogeneità geochimica dei materiali.

### INTERPRETATION OF QUALITY CLASSES: CHARACTERIZATION OF DREDGED SEDIMENT

The marine sediment characterization plan must be carried out in light of D.M. 173/2016. The sampling plan and characterization strategies have been prepared according to the characterization Path I proposed in the Ministerial Decree and have been designed in accordance with the provisions of the Port Regulatory Plan. **Figure 2.7** shows the Characterization paths provided by D.M. 173/2016.

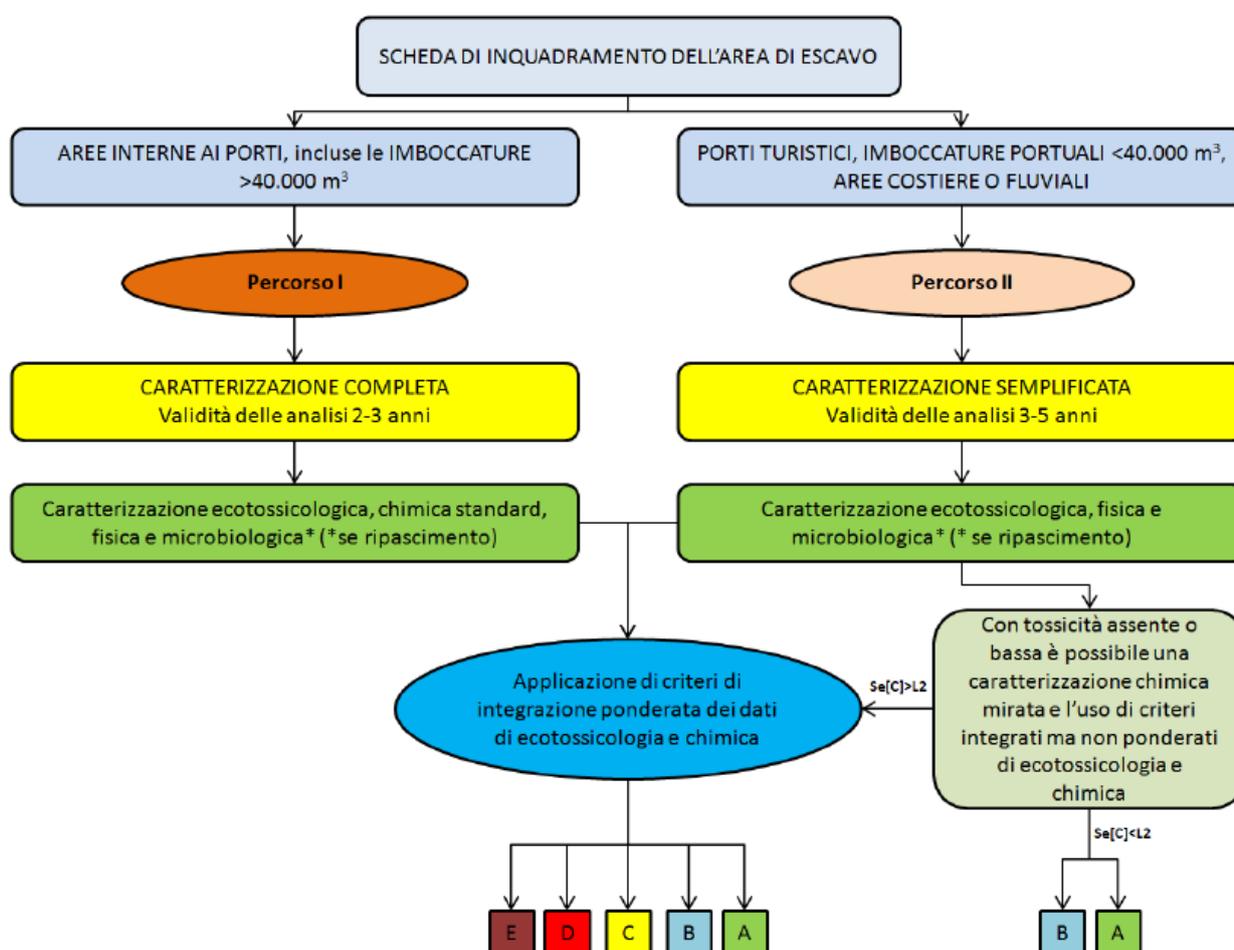


Figure 2.6 - Characterization paths provided by Ministerial Decree 173/2016 (in Italian)

The results of the analyses and the related quality control measures, as well as the analytical methodologies used for each chemical parameter, must be reported on the test reports issued by the accredited laboratories, as well as the following information:

- Recovery percentage compared to certified standard materials
- Limit of quantification or LOQ (guaranteeing at least those reported in [Table 4.2](#) and the technique with which the LOQ was quantified)
- Extended uncertainty
- QA/QC assessments

**Table 2.2 -** Chemical and ecotoxicological parameters researched according to the Technical Annex to the Ministerial Decree 173/2016 (in Italian)

PARAMETRO	SPECIFICHE	LIMITE DI QUANTIFICAZIONE (LOQ)
Metalli e metalloidi	As, Cd, Cr <sub>tot.</sub> , Cr VI, Cu, Hg, Ni, Pb, Zn, V, Al, Fe	0,03 mg/Kg (Cd, Hg) 1 mg/Kg (altri)
Idrocarburi Policiclici Aromatici (IPA)	Acenaftilene, Benzo(a)antracene, Fluorantene, Naftalene, Antracene, Benzo(a)pirene, Benzo(b)fluorantene, Benzo(k)fluorantene, Benzo(g,h,i)perilene, Acenaftene, Fluorene, Fenantrene, Pirene, Dibenzo(a,h)antracene, Crisene, Indeno(1,2,3,c-d)pirene e loro sommatoria	1 µg/Kg
Idrocarburi C>12	Nessuna specifica	5 mg/Kg
Pesticidi Organoclorurati (OCP)	Aldrina, Dieldrin, Endrin, α-HCH, β-HCH, γ-HCH (Lindano), DDD, DDT, DDE (per ogni sostanza la somma degli isomeri 2,4' e 4,4'), HCB, Eptacloro epossido	0,1 µg/Kg
Policlorobifenili (PCB)	Congeneri: 28, 52, 77, 81, 101, 118, 126, 128, 138, 153, 156, 169, 180 e loro sommatoria	0,1 µg/Kg
Carbonio organico totale o sostanza organica totale	Nessuna specifica	0,1 %
Composti organostannici	Monobutilstagno, Dibutilstagno, Tributilstagno e loro sommatoria	1 µg/Kg
Sommatoria T.E. PCDD, PCDF (Diossine e Furani) e PCB Diossina Simili	Elenco di cui alle note della tabella 3/A di cui al D.Lgs. 172/2015	D.Lgs 172/2015
Ecotossicologia	selezionato un saggio biologico tra le tipologie 1, 2 e 3	

With reference to the eco-toxicological part, biological tests must be performed on all samples intended for analysis. The results must be reported on the test reports issued by the accredited laboratories, indicating the test methods and statistical results ([Table 2.3](#)).

**Table 2.3 -** Physical parameters searched according to table 2.6 of the Technical Annex to Ministerial Decree 173/2016 (in Italian)

PARAMETRO	SPECIFICHE	UNITÀ DI MISURA
DESCRIZIONE MACROSCOPICA	Colore, odore, presenza di concrezioni, residui di origine naturale e/o antropica	-
GRANULOMETRIA	Frazioni granulometriche al 1/2φ Dove φ = - log <sub>2</sub> (diametro in mm/diametro unitario in mm)	%
MINERALOGIA	Principali caratteristiche mineralogiche	%

Finally, microbiological analyses must be performed on surface samples, as reported in [Table 4.4](#). The results, including data relating to positive controls (reported to the laboratory control chart), in tabular summary form, must be reported and discussed in a specific Technical Report generally produced by the testing laboratory itself.

**Table 2.4 -** Microbiological parameters researched on surface sediments according to the Technical Annex to Ministerial Decree 173/2016 (in Italian)

PARAMETRO	SPECIFICHE	UNITÀ DI MISURA
MICROBIOLOGIA	Conta Enterococchi Fecali; Conta Clostridi solfito-riduttori; Ricerca Salmonella spp; Conta Coliformi Totali; Conta Escherichia coli; Conta Lieviti e ifomiceti; Conta Stafilococchi	-

The quality classification of the analyzed sediments must be carried out on the basis of the chemical and eco-toxicological analyses, on the basis of the "Weighted integration criteria, as reported in table 2.7 of the D.M. 173/2016 ([Table 2.5](#)).

Table 2.5 - Sediment Quality Classification According to the Weighted Integration Criteria (DM 173/16)

Classe di pericolo ecotossicologico elaborato per l'intera batteria (HQBatteria)	Classificazione chimica	Classe di Qualità del materiale
Assente	HQC (L2) ≤ Trascurabile	A
	Basso ≤ HQC (L2) ≤ Medio	B
	HQC (L2) = Alto	C
	HQC (L2) > Alto	D
Basso	HQC (L1) ≤ Basso	A
	HQC (L1) ≥ Medio e HQC (L2) ≤ Basso	B
	Medio ≤ HQC (L2) ≤ Alto	C
	HQC (L2) > Alto	D
Medio	HQC (L2) ≤ Basso	C
	HQC (L2) ≥ Medio	D
≥ Alto	HQC (L2) ≤ Basso	D
	HQC (L2) ≥ Medio	E

ATTENTION\* the table refers to the previous priority classifications recently updated following the externalization of the DM 173/16. In general, the options remain the same and the color indications summarizes the alternatives in light of the new quality classification (A1-C2 → A-E)

According to the frequently cited manual, the management options that can be pursued are direct consequences of the quality status resulting from the characterization of the samples. Table 2.6 provides a summary of the possible alternatives for the different quality classes.

Table 2.6 - Quality class table (APAT-ICRAM, 2007, in Italian) \*

Classe	Opzioni di gestione
A1	Sabbie (pelite < 10%) da utilizzare o ricollocare secondo la seguente priorità: 1. Ripascimento di arenili (previa verifica compatibilità con il sito di destinazione); 2. Ricostruzione di strutture naturali in ambito marino costiero comprese le deposizioni finalizzate al ripristino della spiaggia sommersa; 3. Riempimenti di banchine e terrapieni in ambito portuale; 4. Riutilizzi a terra (secondo la normativa vigente); 5. Deposizione in bacini di contenimento (es. vasche di colmata); 6. Immersione in mare.
A2	Materiale da utilizzare o ricollocare secondo la seguente priorità: 1. Ricostruzione di strutture naturali in ambito marino costiero compresa la deposizione finalizzata al ripristino della spiaggia sommersa (solo nel caso di prevalente composizione sabbiosa). 2. Riempimenti di banchine e terrapieni in ambito portuale; 3. Riutilizzi a terra (secondo la normativa vigente); 4. Deposizione in bacini di contenimento (es. vasche di colmata); 5. Immersione in mare.
B1	Materiale da utilizzare o ricollocare secondo la seguente priorità: 1. Riutilizzi a terra (secondo la normativa vigente); 2. Deposizione in bacini di contenimento che assicurino il trattenimento di tutte le frazioni granulometriche del sedimento (incluso il riempimento di banchine).
B2	Materiale da utilizzare o ricollocare secondo la seguente priorità: 1. Riutilizzi a terra (secondo la normativa vigente); 2. Deposizione all'interno di bacini di contenimento con impermeabilizzazione laterale e del fondo. 3. Smaltimento presso discarica a terra.
C1	Materiale da sottoporre a procedure di particolare cautela ambientale secondo la seguente priorità: 1. Rimozione in sicurezza e avvio di specifiche attività di trattamento e/o particolari interventi che limitino l'eventuale diffusione della contaminazione; 2. Rimozione in sicurezza e deposizione in bacini di contenimento con impermeabilizzazione laterale e del fondo. 3. Rimozione in sicurezza e smaltimento presso discarica a terra
C2	Materiale da sottoporre a procedure di particolare cautela ambientale la cui rimozione e gestione devono essere valutate caso per caso.

## DREDGING OBJECTIVES

Dredging activities and scenarios have evolved slowly over the centuries, gradually moving from experience-based applications to increasingly advanced interventions, fueled by equipment that follows the pace of technological evolution and by projects based on mathematical and numerical models.

The main objective of dredging has always been the maintenance of navigable depths in ports or canals, while more current issues include reclamation, construction and maintenance of maritime infrastructure on which the economic well-being of many countries is based.

The most recent need is to address these realities also from an environmental point of view, in order to mitigate the negative effects associated with each dredging project. The amount of material made available by each intervention is considerable, which is why the current tendency is to promote its beneficial use, from the creation of construction materials, to the nourishment of eroding beaches or, for example, to the protection of salt marshes.

In general, the term dredging refers to a wide variety of different activities; the main objectives are essentially four:

1. economic, linked to the creation of the seabed necessary for the transit of ships in the access channels to ports and in port basins;
2. recreational, carrying out beach nourishment works;
3. coastal protection and sea defence works;
4. defence, understood as flood prevention through the construction of environmental protection works and the removal of polluted material.

Although less commonly, dredging is used to find minerals and precious metals or to remove the excess part that covers them. Three main categories can therefore be recognized: main, maintenance and corrective works.

### MAINTENANCE DREDGING

This type of activity concerns the removal of silting from the bed of the canals, a natural phenomenon, in order to maintain the design depth for navigation in the canals and in the ports. The main characteristics are:

- Variable quantities of material;
- Soft, non-compacted soil;
- Possible presence of contamination;
- thin layers of material;
- Work to be done with fixed periodicity.

Since maintenance dredging is most often needed in areas that are artificially deepened for navigation, it does not necessarily impair the natural environment ([Giame and Mosca, 2009](#)). The greatest potential for negative environmental impact is the disposal of dredged material and the high amount of suspended material during the dredging phase, which may eventually include dispersion of pollutants.

The problem of turbidity can be controlled with appropriate procedures and means. This is aggravated by the need to do this type of intervention on a regular basis, since silting is a cyclical phenomenon. The polluting content of the material that has to be excavated can have a significant impact on the environment.

Many cities have long allowed sewage and industrial waste to be poured into canals, causing canal beds to become impregnated with numerous pollutants that have entered the water system.

Dredging can spread the particles to which the contaminants are attached and increase the speed with which they spread. The extent of this phenomenon depends on the type of equipment used and the care taken by all those involved in these operations.

## CAPITAL DREDGINGS

They involve the creation of new or improved facilities such as port basins, deeper navigation in canals, a lake or a reclamation area for industrial or residential purposes. The following features generally characterize these projects:

- Repositioning of large quantities of material;
- Compact soil;
- Undisturbed soil layers;
- Low contamination content;
- Layers of significant thickness;
- Non-repetitive dredging activity.

Clearly, a negative environmental effect of these operations is often the destruction of natural habitats (drainage of wetlands, disposal of dredged material in biologically sensitive areas...) (Giaime and Mosca, 2009). However, on the other hand, additional wetlands or tidal zones can be reconstructed and important areas can be protected from erosion.

How exactly the environment is affected is largely determined in the design phase. The spread of chemical contaminants absorbed by the dredged material is generally of little concern if the material to be dredged is unaltered. The environment is best considered when a comprehensive analysis of the environmental consequences is integrated into the design phase. It is at this stage that the main remedies can be taken, such as improved design, suitable selection of dredging facilities and informed selection of sites. Furthermore, the beneficial reuse of dredged material can have a largely positive effect on the whole environment in the project area.

## ENVIRONMENTAL\REMEDIAL DREDGING

It should be noted that both infrastructure and maintenance works can have a beneficial effect in terms of removing contaminated material. Remedial work, purely for the purpose of cleaning the dredging area, is not always considered as a separate type of dredging and has distinctive characteristics. A company to correct past actions that, in many cases, have strongly determined the contamination of the sediments carries it out. This type of remedial dredging requires the careful removal of the dredged material and is therefore linked to its further treatment, reuse and repositioning. Its characteristics are:

- limited quantities of dredged material;
- highly contaminated contents;
- soft, non-compact material;
- requirement of periodic interventions.

It is therefore work aimed at remedying an existing critical situation, which is carried out with great care and which does not significantly damage the environment in other ways. A prerequisite for a dredging operation of this type is the removal of contaminated material before the start of any type of intervention. Each of these three types of intervention has different purposes, although none is aimed at dredging for its own sake; it is a means to an end such as deepening a channel, removing contaminated material, or creating safe zones for commercial or industrial development. To meet these intentions, the dredging industry has developed a wide variety of means, each with specific characteristics.

## PHASES OF A DREDGING CYCLE

The characteristics of a dredging cycle vary considerably from project to project. However, it is possible to identify a number of different phases that are common to most projects in relation to the equipment used for each execution. The phases are reported below (Smith, 1998).

### PHASE 1 - EXCAVATION OR REMOVAL PHASE

This process involves the removal of sediments and/or rocks from the bottom. A special machine, a dredge, is used for these purposes, through mechanical or hydraulic action or a combination of the two. The most significant **environmental effects** that occur during this process are reported in the following.

- Increase in suspended sediments: during the excavation phase, the cohesion of the in-situ material is loosened and part of the material can be brought into suspension due to the rotational or cutting movement. The amount of material brought into suspension depends on the energy applied in the excavation and on the way in which the material is lifted to the surface.
- Mixing of the layers: when equipment necessary for thick layers is used, equipped with a combined vertical and horizontal cutting movement, it is difficult to avoid mixing the layers themselves. If the movement of the equipment, on the other hand, is only horizontal, it is easier to control the thickness of the layers.
- Dilution (in the case of hydraulic dredging): to facilitate transport of the excavated material, water is added during the cutting and suction phases. The water/soil ratio varies depending on the type of dredge. This variable is influenced when the thickness of the layer to be removed is small compared to the minimum thickness that the dredge can remove.

### PHASE 2 - LIFTING THE MATERIAL

During the second phase of a dredging cycle, the removed material is lifted to the liquid surface; this operation can be performed mechanically or hydraulically. In the first case the material is lifted using a grab (bucket dredgers, scoop dredgers or clamshell dredgers); in the second case the hydraulic dredgers (disintegrator suction, stationary suction and self-propelled suction) use a suction pipe. The excavated material is sucked from the suction mouth using centrifugal pumps.

The material is then further lifted by means of the suction pipe towards the pump and from there, through the discharge line, it is sent to the dredger's hold.

The **environmental risks** at this stage are different.

- Release of suspended sediments: in the case of mechanical excavation with an open bucket, the dredged material is in direct contact with the water, which can cause dilution and an increase in the content of the suspended sediments in the overlying water column.
- Release of loose layers: with hydraulic transport there are potential problems related to the area of the suction mouth. If the suction capacity is lower than the excavation capacity of the dredger, there is a release of material that forms a layer, which remains on the seabed. The same effect is observed when the disintegrated material slowly falls into the water column, reaching the suction depth when the suction mouth has moved away.
- Density of the material: problems can arise with hydraulic transport, as this method requires the addition of water to obtain a density of the mixture that is suitable for pumping. The coordination between the excavation capacity and the pumping capacity is crucial: if the latter is too high, the density of the mixture in the suction line becomes too low. This causes problems of dehydration during the disposal or treatment phase, which is even more worrying in the case of contaminated material.
- Overflow during the loading of the hopper or barges: the overflow of excess water inevitably carries the sediments into the surrounding waters. This is important especially when treating contaminated materials.

### PHASE 3 - TRANSPORT OF DREDGED MATERIAL.

The third phase of a dredging cycle is the horizontal transport of the excavated and lifted material from the dredging area to the treatment or final storage area. This can be achieved mainly with one of these methods: 1) transport in the hold of the dredgers themselves or on barges; 2) pumping through pipelines; 3) transport on trucks and conveyor belts.

Each method is linked to the type of dredger used: transport by barge is generally associated with mechanical excavation, while transport by pipeline is used with hydraulic dredgers. The **environmental effects** related to transport can be summarized as follows.

- **Safety:** when using open barges for transport, the crew may come into direct contact with the dredged material. This is not a problem in a normal dredging project, but in the case of contaminated material a health risk may arise.
- **Dilution:** this is more likely to occur with the use of hydraulic dredges where a maximum density is imposed to allow discharge, driven by centrifugal pumps, through pipelines.
- **Spillage:** the greatest risk is the loss of material in the joints between pipelines or the loss from the barges themselves, especially in difficult weather conditions. Leakage may also occur if the bottom of the barge is damaged or poorly sealed;
- **Noise and air pollution:** this is a more significant effect in the case of transport by barge than in the case of transport by pipeline.

Figure 2.8 shows the sequence of operations during the transport phase.

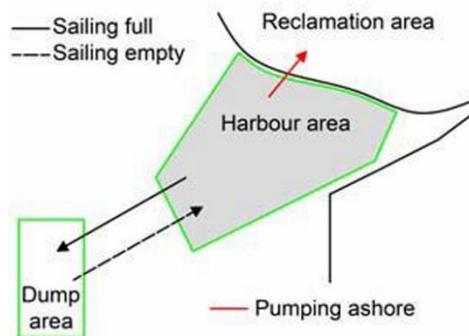


Figure 2.7 - Sequence of operations during the transport phase

### PHASE 4 - PLACEMENT OF THE MATERIAL

The final stage of a dredging project is the repositioning of the excavated material to its final destination or to an intermediate site for treatment operations. The possibilities at this stage are considerable: - reclamation of an area; - nourishment; - creation of wetlands; - repositioning on land; - repositioning in a quarry; - repositioning at sea.

The following effects due to repositioning are noteworthy.

- **Occupation of spaces:** the major effect, especially in the case of positioning on land, is the occupation of land and the alteration of the natural habitat. The same occurs underwater, with a less visible effect.
- **Dispersion of the deposited material:** in underwater storage sites, depending on the depth of the sea, the effects of waves and currents can cause the dispersion of the finer material. On land, however, the same action is carried out by wind or rain;
- **Noise and air pollution:** the placement operation, especially if carried out by vehicles or other earth-moving machines, can generate noise and pollution problems;
- **Quality of underground water:** if the choice of the storage area is wrong and the protective measures are lacking, the loss of material can damage the underlying aquifer.

## SEDIMENT REMOVAL: THE DREDGES

Dredging equipment should be chosen according to the type of material to be dug, the presence of wave motion in the excavation area and the overall amount of excavation to be done. Dredgers are of different types and sizes and include machines operating in water and those on land. Dredging equipment is classified according to the excavation operations and can be grouped as follows (Smith, 1998).

- mechanical dredgers;
- hydraulic dredgers;
- special low-impact dredgers;
- other types of dredgers.

The identification of the most suitable dredgers can also be made based on the propulsion, choosing between self-propelled or stationary machines. It is also necessary to take into account a combination of factors such as the type of physical environment, the positioning method and the distance from the positioning site and finally the nature, quantity and level of contamination of the material to be dredged.

### HYDRAULIC DREDGERS

They are generally used in the presence of weakly compacted material and mainly use centrifugal pumps.

The material is collected and transported in sludge or liquid form by means of suction pipes that operate as a result of the depression that forms in the collection area.

Hydraulic dredges are often also used to indicate those dredges whose operation is achieved by coupling both types, in which the excavation system is mechanical and the material transport system is hydraulic. These dredges are designed to meet specific needs, as they allow well-compacted materials to be dredged while limiting problems related to turbidity and the escape of particles into the water column.

The concentration of solids collected is intermediate between that obtained with the mechanical and hydraulic techniques. Among the many disintegration mechanisms that are often applied to this type of dredger, there is also the use of powerful water jets near the suction head, which significantly improves the excavation capacity in the presence of more compacted material.

The dredged material is usually deposited in the unloading area through a special pipe or is fed into the hold of the dredger itself, from which it can be subsequently unloaded through an opening in the bottom. Hydraulic systems are faster than mechanical ones and cause less suspension of material since, during dredging operations, once captured by the suction head, they do not give rise to many leaks into the surrounding water column. Three main types of hydraulic dredgers can be identified.

#### ➤ Suction Dredgers - Stationary suction dredgers (SD)

They are used for excavation operations of unconsolidated soils made up of sand or gravel. Their main limitation is that they produce shallow excavations and for this reason they are rarely used for the construction of ports or canals. They require anchors and moorings that can hinder navigation. It is a very economical tool when it can flow directly through pipes into the filled area (Figure 2.9).

#### ➤ Cutter Suction Dredgers (CSD)

They are equipped with a cutting head that increases the dredge's material removal capacity. They operate by advancing on two anchoring pylons fixed in the ground: during the dredging operation, the cutting head is moved by mechanical winches and describes semicircular arches that cause incisions in the seabed of a depth of about ten centimeters. The material is then captured by the head of the suction pipe and is then pumped to the shore through pipes or placed on barges.

They are properly used in the case of well-compacted materials such as clay, sand or soft rocks (Figure 2.10).



Figure 2.8 - Stationary suction dredger

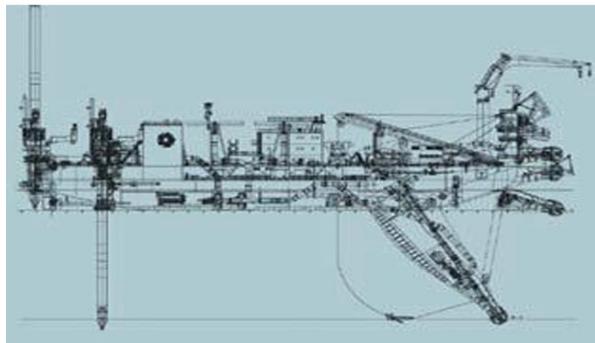


Figure 2.9 - Dredger underway (left) - Section of a suction dredger (right)

### ➤ Trailing Suction Hopper Dredgers (TSHD)

They operate in such a way that as they move, they make a suction head crawl on the seabed which picks up the material and puts it into the hold. This type of dredger can navigate autonomously without the need for tugs or moorings, allowing the transport of the load even over long distances. They are suitable for dredging all non-rocky solids. The material is then unloaded by gravity by opening the bottom of the vessel or is pumped to the shore via pipes. Thanks to their high working and production speed, they are frequently used in nourishment or dry land creation projects and in maintenance dredging, but they still need adequate sea-beds and liquid surfaces of sufficient size (Figure 2.11).

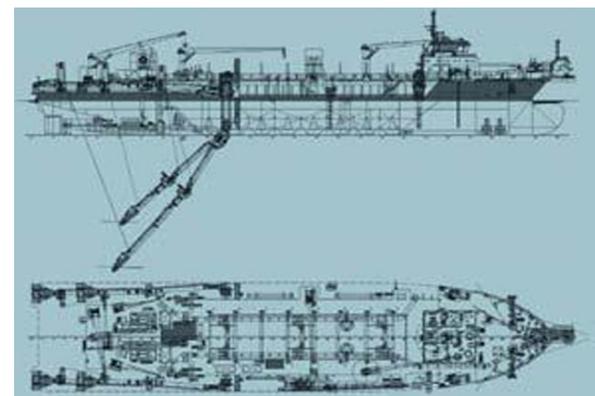


Figure 2.10 - Dredger underway (left) - Section and planimetry of a TSHD dredger (right)

## MECHANICAL DREDGERS

They are used to remove gravelly, hard or compact material using technologies similar to land excavation methods. They are suitable for work in areas of limited size. Mechanical dredges use excavation and transport systems that can generally be identified with a clamshell bucket, mechanical spoons or buckets where the collected material passes through the entire water column meeting the surrounding environment. The dredged material is then transported by pontoons and barges or by hopper boats with an opening on the bottom capable of travelling long distances. The cohesive sediments dredged and transported with this method generally remain intact throughout the process, with large quantities that maintain the density and structure that they had in situ. The main types of mechanical dredges are listed below.

### ➤ Bucket Ladder Dredgers (BLD)

They use a series of containers, buckets', mounted on a self-propelled belt. By rotating, they collect and drag the material to the surface and then unload it onto buckets placed alongside the dredger. They can be used for a wide variety of sediments including those formed by soft rock. They have a low yield in clay and not very high in sand due to the buckets not being completely filled. They have fallen into disuse due to their low production speed, the high level of noise and also the need to have large moorings that are an obstacle to navigation. They also have the defect of causing a high dispersion of the material in the water column, also due to the fact that the air trapped in the buckets during the ascent tends to push out part of the collected material (Figure 2.12).

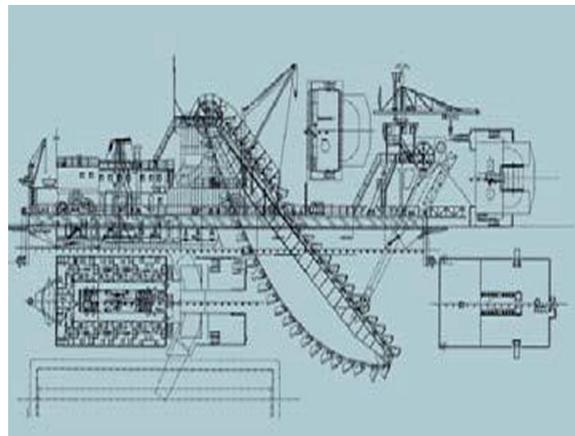


Figure 2.11 - Dredger underway (left) - Section of a Bucket ladder dredger (right)

### ➤ BackHoe Dredgers (BHD)

They work similarly to mechanical earth excavators: they are in fact characterized by a scoop excavator installed on the deck of a vessel equipped with steel anchoring pylons. The excavated material is brought to the surface and deposited on barges for transport. They are tools of limited use, with high operating costs, used for the excavation of compact, heterogeneous material but whose limitation is the fact that they cannot reach very great depths (Figure 2.13).



Figure 2.12 - BHD dredger in action

### ➤ Grab Dredgers (GD)

They are equipped with a grab bucket operated by a mechanical arm located on the deck of the vessel. The dredging operation is carried out by lowering the bucket to the seabed, closing it and raising it to the surface where its contents are unloaded onto buckets placed next to the dredger. It is a flexible piece of equipment, suitable for carrying out modest quantities of work, given that it has high unit costs; it is particularly suitable for excavation work in areas that are difficult to access.

Another limitation is that it produces irregularities in the shape of the seabed (Figure 2.14).



Figure 2.13 - Grab bucket dredger

### OTHER TYPES OF DREDGERS

Among the specialized dredging techniques in which there is no need to lift the material to the surface before it is transported, the so-called "hydraulic dredges" stand out. Horizontal transport is in fact obtained by natural forces, but in a less controlled way than the other methods just described. Two main types of dredgers fall into this category: hydraulic injection dredgers and underwater ploughshare dredgers. Environmental tolerability, in the use of this system, should always be considered in the preliminary phase of a dredging project so that appropriate contractual conditions can be included.

### ➤ Water Injection Dredgers (WID)

This equipment throws a large amount of water on the surface layers of the bottom, as a result, the density of the material decreases and the upper part rises slightly. The material starts to move naturally until it reaches a state of equilibrium. In the case of a slope, even a small one, in the dredging area, the transport distance can be significant. The material is deposited in an adjacent area with a lower slope. WIDs are dredgers that cannot be used in environmental projects because the material is not physically removed but simply moved to another place, in a rather uncontrolled and less predictable way. However, they can be used with some advantages in those areas less sensitive to this type of problem (Figure 2.15).

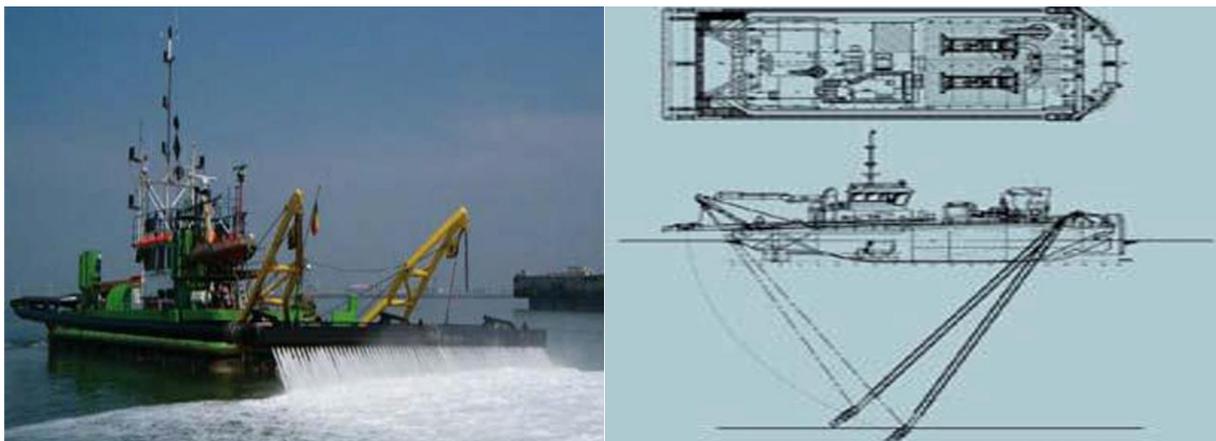


Figure 2.14 - Dredger underway (left) - Section and planimetry of a water injection dredger (right)

### ➤ UnderWater Plough (UWP)

Characterized by a large frame that is pulled along the bottom by a tugboat; the frame is equipped with blades that scrape the surface layers of the bottom. The excavated material remains in front of the blades and is then pushed forward until the volume of the collector is full. At this point the process must be stopped otherwise the material escapes from the collector and becomes partially suspended.

The UWP system is mostly used in maintenance dredging in tidal basins, where large quantities of sediment are deposited. The material is either pushed back towards the main current, so as to reintroduce it into the natural transport process of the channel, or it is moved to areas where other dredging equipment does not have access and where it can subsequently be removed by normal dredging.

This type of operation cannot be carried out in environmental dredging projects as it is impossible to control the transport and deposit process and the material is not removed from its natural system. In other projects, however, it can be a valid alternative, preferable for lower operating costs ([Figure 2.16](#)).

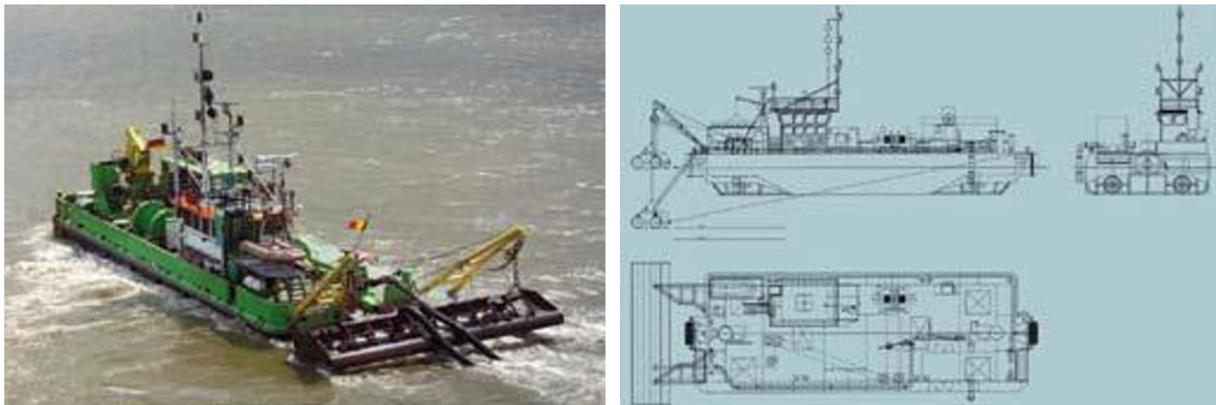


Figure 2.15 - Dredger underway (left) - Section and planimetry of a UWP dredger (right)

### ADVANCES IN DREDGING EQUIPMENT

In addition to the development of new machines, dedicated to infrastructural dredging, a significant push has been given to the enhancement and optimization of existing tools.

In recent years, many changes have been implemented in relation to the constraints imposed on dredging activities, in response to considerations and limitations desired regarding the protection of environmental ecosystems. This has led to a general rethinking, both from a conceptual and technical point of view, of all dredging activity; it has determined a continuous adaptation of traditional machinery to improve their ability to cope with new constraints. The major innovations that have driven these changes are:

- Increased dredging precision in order to reduce dredged volumes;
- Reduction of suspended sediment production in the dredging and storage area, in order to avoid problems arising from slightly or heavily polluted material;
- Improved on-board monitoring and control possibilities to enable the crew to recognize and correct effects and trends in the initial phase;
- Development of 'layer by layer' excavation methods to achieve selective dredging of layers with different contamination contents;
- Reduction of material losses from easily erodible layers: this prevents dispersion problems in the case of polluted material;
- Increase in the transport phase of the density of the dredged material, so as to reduce the volume sent for further treatments and so as to reduce the time for the full consolidation and maturation of the material in the onshore storage areas;
- Increase in automatic control, to ensure a continuous process and allow the crew to concentrate on the main controls, leaving the repetitive operations to the automatic control system.

Some "innovative systems for all types of dredgers" are listed below and briefly described.

### ➤ **Dredging Information System**

There has been considerable progress in recent times in monitoring dredging activities, both on board the vessels using a continuous data recording system, and in the offices using the Dredging Information System. These systems continuously record a large number of variables such as dredging depth, position, volumes, concentration, voids, pressure, rotation speed, energy consumption. The data is processed automatically and sent to both an automatic control and guidance system, and to a real-time feedback system for use by the dredging manager and supervisor.

### ➤ **Automatic control systems**

The development of information and monitoring systems has led to an increase in the use of automatic control systems on board dredgers. This allows the project manager to focus on the creative part, namely the optimization and improvement of the dredging cycle. A direct consequence is the continuous need for accurate measurement systems for all the variables that enter into the process: the quality of the information available is thus better.

### ➤ **Degassing system**

A factor that limits the density of the mixture pumped by centrifugal pumps is the gas contained within the bottom material. When the gas content is very high, the risk of cavitation, following the rapid increase in pressure within the sediment mixture, is very high. It is therefore necessary to reduce the gas content before the dredged material enters the suction pump. This technique is widely used by various manufacturers in the dredging field; the result is an increase in density in the transport pipeline or in self-propelled suction dredgers and a consequent decrease in the volumes to be deposited.

### ➤ **Control and monitoring systems**

A concrete improvement in the precision of mechanical dredging equipment has been achieved thanks to the continuous monitoring of the position of the bucket in the submerged state using dedicated software. The most sophisticated systems memorize the dredging operations, avoiding having to dig several times in the same place.

In general, there are additional systems to define the excavation depth in advance, in order to avoid different depths from one cycle to another. Systems have also been developed that automatically control the movement of the pontoon in compliance with a predefined curve. The most sophisticated positioning systems allow very accurate bucket movements characterized by positioning errors of a few centimeters. These results are obtained thanks to the installation of D-GP on the dredge arm, which allow the movements of the cutting head to be monitored and instantly corrected automatically or manually. Thanks to these improvements, mechanical dredgers can also be used for environmental dredging projects, which was intolerable in the past due to the imprecision of the excavation profile. This introduced the possibility of excavating contaminated material with densities equal to those in situ.

### ➤ **Green TSHD**

One of the major constraints for TSHD dredgers is overflow, i.e. discharge into the sea via surface spillways: this practice generates an increase in turbidity in the water column, characterized by a high content of fine sediments in the discharged mixture. The simplest but also uneconomical way to overcome this problem is to stop dredging when the dredger is full; therefore, new technologies have been introduced.

- Controlled dumping to improve the accumulation capacity of the dredger.
- Controlled dumping, via a guidance system in the suction pipe, which directs the excess water to the lowest part of the water column.
- Trailers with better characteristics for containing the material.
- Reuse or recirculation of excess water inside the jets installed on the dredger. This has made it possible to significantly reduce the excess water discharged into the sea and the dispersion of the finest sediments in the dredging area.
- Use of submersible pumps, thus obtaining a higher density of the material to be dredged.

## TRANSPORT OF DREDGED MATERIAL

### TRANSPORT VIA PIPELINE

This type of transport ([Figure 2.17](#)) is fundamentally an environmentally friendly method and, compared to other transport methods, it has low energy consumption and, in addition, noise and air pollution are almost non-existent. It is generally used for the transport of dredged material, whether it is uncontaminated or polluted: it is therefore a clean system as it takes place within a closed circuit. The only points of contact with the external environment are the suction mouth and the outlet in the storage area: between these two sections there is no possibility of contact between the transported material and the environment unless a break occurs in the pipeline itself ([APAT, 2004a](#)). The total breakage of a pipeline is a very rare phenomenon and leakage control can be investigated when the transported material is heavily contaminated. In most cases, however, the impact due to a small leak can be neglected and is less significant than the potential risk of contamination of other transport methods. Some measures have been employed to improve this transport system, and others could be developed.

- Recent automatic control systems include a pump-monitoring device and a guidance system for a smoother flow process with lower peak values of the mixture density. Physical reasons limit the highest peaks of density and this allows obtaining an average density of the mixture in the pipeline.
- Regular interruptions in the dredging process at the end of each oscillatory movement and during the anchoring and loading phases of the material, are the main causes of the addition of water to the transport pipeline; the introduction of a series of bearings between the suction and discharge sections, prevent the operator from interrupting the suction phase during dead periods. This allows avoiding interruptions in the discharge phase of the material during periods of inactivity.
- The use of high-density pumps significantly reduces the need to add water for transport although, as a defect, they have rather limited outlet capacities.
- In case the transport pipeline requires the use of an unloading barge, the process of returning the water from the storage site to the dredger and the recirculation of the water for unloading should be considered. The biggest disadvantage of this method is the need to mix the dredged material with the transport water and this increases the volume needed for storage or subsequent treatment, which, in case of contamination, can be a serious problem.



Figure 2.16 - Example of transport via pipeline.

## *BARGE TRANSPORT*

The second type of transport, frequently used in dredging works, is by barge or container: in this case, the dredged material is deposited hydraulically or mechanically inside a vessel. Horizontal transport between the dredging site and the storage or treatment area is therefore done by navigating a barge (APAT, 2004a). This system causes noise and air pollution and maritime traffic problems. The main advantage is that water is not needed for transport as the excavated material can be taken at its original density, which can therefore be maintained, with the exception of the TSHD, which, with the use of hydraulic pumps, conveys the material from the bottom to the inside of the vessel. The most obvious risk comes from the fact that most barges are open and this involves the possibility of the material leaking out. There is also a risk of crew contact with the dredged material, which can present a problem if the dredged material is contaminated. An important element in control is to ensure regular inspection of the barges, as well as their maintenance. New approaches have been developed to improve the aspects just mentioned.

- To avoid material spilling from the barge during transport, it is useful to cover it with a sheet, or to continuously remind the workers to leave sufficient space (at least 50 cm) above the loaded sediments. Another possibility is to leave the sediments still for a certain period after the loading phase: the water can be pumped out before the transport begins.
- - For the unloading procedure, the barge is emptied by opening the bottom in an underwater storage area or by using another vessel that unloads the material hydraulically, which however requires considerable dilution in the suction phase. To avoid this, it is better to use the mechanical system, so that the material maintains its density.

## *ROAD TRANSPORT*

Road transport should be considered when the destination site of the material is not near a navigable waterway. The opportunities for this type of transport are limited, in any case, the advantages consist in the fact that the vehicles can be mechanically loaded with any density and that the choice of destination is flexible. The main disadvantage derives from the high number of vehicles needed to transport the material and the consequent pollution produced, which is certainly greater than that produced by transport by pipeline.

This type of transport can therefore be used in certain situations:

- where the material is highly polluted and the cost for the treatment of the transport water is high;
- where the excavation is carried out mechanically;
- where the dredged material has different characteristics and therefore different destinations.

## DEPOSIT OF DREDGED MATERIAL

The deposition of the dragged material at the storage site is another important phase in the dredging process, which can potentially have significant effects on the environment: it is necessary to select these areas and the related infrastructure in the most appropriate way. Furthermore, the equipment and techniques used for the storage of the material have an influence on the overall environmental effects of dredging [APAT \(2004a\)](#).

### GROUND STORAGE

One option for placing the dredged material is on land, within a confined area surrounded by embankments: this system is applied when the material must be used on land or when it is contaminated and therefore must be deposited in a storage area on land. To send the material to land, pumps are used, installed on board the dredgers, which, through pipelines, convey it to the chosen area. With this procedure, the most significant environmental effects are:

- burial of surfaces;
- change in topography;
- loss of (contaminated) transport water in the sub-surface layers of the soil.

A problem that can arise at this stage is the breaking of the embankments or the overflow of the material above them: the surrounding environment will then be damaged. To avoid all this, an adequate design of the embankments and control of the water level inside them is required. Another problematic item is the evacuation of the excess transport water: it contains a small part of fine material that is being deposited in the storage area and, if this is contaminated, the effect on the environment can be dangerous. Furthermore, the quantity of fine material that passes through the terminal section can generate blockages in the channels used to remove the transport water. The construction of reclaimed basins can be an additional safety measure in which very restrictive limitations must be imposed on the content of suspended sediments relative to the transport water. It would also be necessary to close the terminal section of the basin during the material deposit phase and stop the work every time the area is filled to its maximum capacity so that, by leaving the material to settle for a few days, the water containing, by now, a smaller quantity of suspended sediments is removed. To avoid interrupting the storage operations, it is advisable to create several reclaimed basins in series, which can then be used simultaneously. In any case, it is advisable to adequately study the environmental conditions of the area chosen for unloading to assess any risks or take the necessary precautions such as, for example, repositioning the material in a less vulnerable area or installing protective coverings such as those in HDPE (High-density polyethylene) or natural materials ([Figure 2.18](#)).



Figure 2.17 - Confined area for the storage of dredged material

## SEA STORAGE

When the dredged material is qualitatively suitable, it can be deposited in the sea, if suitable areas are available. Generally, underwater storage occurs after horizontal transport on a barge: the vessel sails directly from the dredging area to the storage area and here the bottom of the vessel is opened so that the material flows onto the riverbed or the seabed. Here too, the choice of a site has a great effect on the environmental consequences of the project. An area with a significant tidal range or stressed by strong currents involves a risk of erosion, resuspension and subsequent dispersion of the material in the surrounding area. In other cases, however, areas such as those just mentioned are deliberately chosen to exploit the currents themselves. Environmental damage can be reduced by using, instead of the opening in the bottom of the barge, a pump connected to a vertical pipe that reaches the bottom to convey the material towards its final destination without contact with the intermediate water layers: in this way, losses of fine sediment and dispersion are significantly reduced. To maximize this result (Figure 2.19), a diffuser can be installed in the terminal section, which has two main purposes (APAT, 2004a):

- Change the direction of the flow of the mixture from vertical, in the duct, to horizontal, on the seabed: this reduces both the flow of the current on the newly deposited layers and the resuspension of the material;
- Reduce the speed of the mixture at the outlet from 4/5 m/s, in normal discharge ducts, to less than 0.5 m/s: this reduces the erosion on the newly discharged layers.

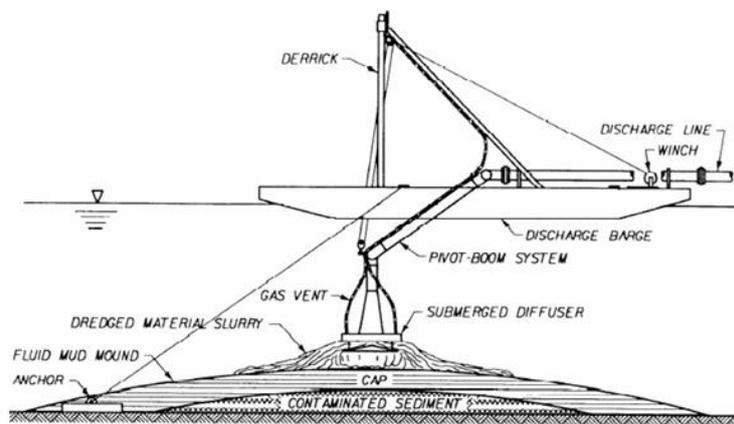


Figure 2.18 - Underwater diffusion system

Another method to reduce the environmental impact of the dumping process is to limit the period during which dumping is permitted: avoid dumping underwater when the tide is at its highest or during seasons when there is intense biological activity in the area (Smits 1998).

## STORAGE TECHNOLOGIES

Storage refers to the operations of disposing of dredged material in a permanent site, structure or basin. Storage can concern both dredged sediments and residues from preliminary treatments and/or treatments of the sediments themselves.

### ➤ Unconfined open water storage

The material is stored in shallow water (< 18m) a short distance from the dredging area; part of the material can be stored close to the coast to protect the coast itself, or can be used for the nourishment of eroded beaches. The main factors to be taken into account are:

- currents and wave motion;
- water depth and bathymetry;
- potential changes in erosion and deposition;
- chemical and biological characteristics of the site;
- other uses of the site that can interfere with confinement.

This technology is applicable only to uncontaminated sediments or treatment residues; it has the advantage of being the least expensive among the storage alternatives.

Figure 2.20 below illustrates the different methods of deposition of the material on the seabed.

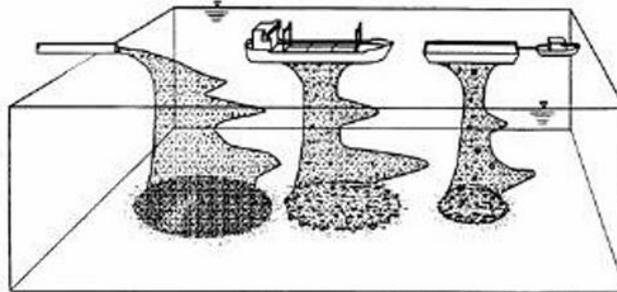


Figure 2.19 - Methods of sediment deposition on the bottom

### ➤ Capping on the bottom

The contaminated material (moderate contamination) is placed on the bottom, on a flat surface to form a pile, and then it is covered with a "cap" of uncontaminated material in order to physically and chemically isolate the contamination. The characteristics of the capping material and its thickness must be such as to guarantee the isolation of the contamination and to resist wave motion and erosion. Capping (APAT, 2004a) determines a significant reduction in the risk associated with sediments, since it provides physical isolation of the latter, protects them from erosion, prevents phenomena of resuspension and transport and finally constitutes a chemical isolation, reducing the dissolution and transport of colloids. The main factors to take into account in the design of a capping on the bottom are:

- characteristics of the contaminated sediments;
- characteristics of the material used for the capping;
- selection of the site, equipment and construction techniques;
- thickness of the capping;
- maintenance and monitoring interventions.

It is important that there is a low erosion potential and that the capping material is not dispersed or mixed with contaminated sediments; therefore, an effective monitoring system is essential to determine the effective isolation of the sediments and to evaluate the need to reinforce the confinement system.

The capping is made with uncontaminated granular material, such as sand, sediments, soil, sometimes, for particular needs, more complex capping are made with multiple layers of different materials and with the presence of geotextiles that have the purpose of preventing the mixing of contaminated sediments with the capping material. Usually, the use of natural sands is preferred since these have an association of fine material and organic carbon content that is very effective in the chemical isolation of contaminated sediments. To provide long-term protection, the capping must be thick enough to effectively separate the contaminated sediments from the aquatic organisms that live and feed in the area of interest; this is achieved by also providing for the use of measures that prevent the colonization and disturbance of the site by these organisms. When designing a capping, consolidation must be taken into account; this phenomenon concerns both the fine granular material that constitutes the "plug", which can undergo consolidation due to its own weight, and especially the contaminated sediments that consolidate due to the weight of the overlying capping. It is therefore important that the design thickness of the confinement system consider this phenomenon in order to ensure a minimum thickness after consolidation.

Contaminated sediments are generally fine material, often with a high-water content and modest shear strength; this last characteristic influences the ability of the sediments to resist localized loads and slips that can cause an unwanted mixing between the sediments themselves and the capping material. To improve the mechanical properties of the "sediments + capping" combination, the latter must be placed slowly, gradually, over the entire area involved: this will avoid displacements, subsidence, mixing with the sediments and resuspension.

The material that constitutes the capping can be placed on site either with mechanical methods, therefore in a dry state through buckets that release the material on site, or with hydraulic methods, in a sludge state, transported through pipes. The hydraulic method is the most precise, even if it is necessary to dissipate the energy needed for the transport before the material is placed on site to avoid the unwanted resuspension of the contaminated sediments. The high costs of this technology are due to the specialized equipment, the capping material and monitoring.

Figure 2.21 shows some frequently used "capping types".

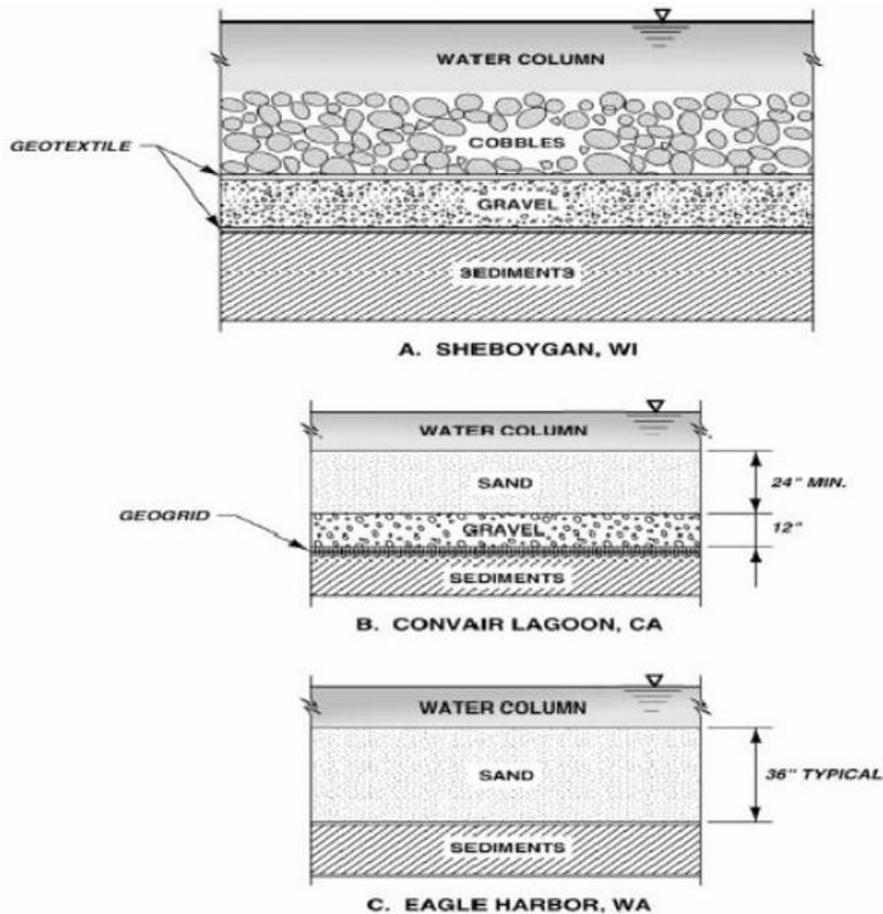


Figure 2.20 - Capping types

### ➤ Natural confinement and capping

The contaminated material is placed in natural or artificial depressions and/or trenches that constitute the lateral confinement of the sediments to which a surface capping is added, which, not protruding above a pile, is less subject to erosion forces. For the creation of the capping, non-contaminated material from the excavation of the overflow pit can also be used. The selective factors, problems and cost analysis illustrated for the bottom capping are perfectly applicable to this type of confinement as well.

## STORAGE WITH ARTIFICIAL CONFINEMENT

In this case, containment is the placement of material in sites or structures designed to contain and control contaminated sediments.

### ➤ Commercial landfills

Dried sediments or residues from pre-treatments and treatments can be dumped in commercial landfills in modest quantities and can be used, as already noted, for daily covering or for the construction of partitions and covers. Before disposal, it is advisable to evaluate:

- the concentration of contamination;
- the distance and cost of transportation;
- the residual capacity of the landfill;
- the solids content of the sediments.

### ➤ Confined Disposal Facilities or CDFs

It consists of the storage, for an indefinite period, of the most contaminated sediments, followed by monitoring the release of contaminants; the degree of containment of this structure is extremely high.

A containment facility must also provide for the drying of the sediments to have greater compaction and maximize space. In the case of dredged and mechanically transported sediments, the design of a CDF ([Figure 2.22](#)) is made on the basis of the volume of material to be stored; if instead there is hydraulic dredging and transport, the design must take into account many more variables, such as the productivity of the dredging, the surface area, the quality of the effluent.

Below are some structural peculiarities of CFDs.

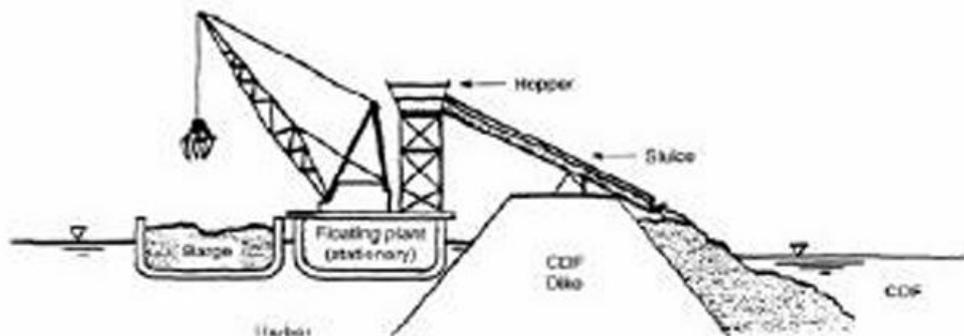


Figure 2.21 - Mechanical storage of sediments

### CDF on land (UCDF)

This type of structure is characterized by good visibility ([Figure 2.23](#)), which is an advantage from a safety point of view; on the other hand, however, the high visual impact creates discontent in public opinion. It is essential to provide isolation measures to reduce the advective transport of contaminants, as well as the risk of leaching; furthermore, it is advisable to guarantee the presence of water in the filling basin in order to preserve anoxic conditions capable of preventing the mobilization of contaminants.

The filling of this type of CDF is rather expensive, in fact, hydraulic systems cannot be used, but must resort to barges; on the other hand, however, the monitoring is relatively easy.

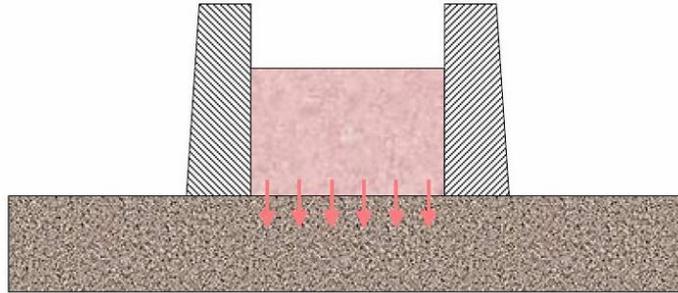


Figure 2.22 - Schematic of CDF on ground

### CDF island/near coast (NICDF)

This type of reclaimed basin guarantees a fair amount of visibility (Figure 2.24), but it is associated with a high visual impact, furthermore if it is built in a stretch of sea, river or open lake it can determine the closure of that area to navigation. As long as the water covers the stored sediments there are anoxic conditions that prevent the mobilization of heavy metals; there is then less dispersion in the surface water thanks to the presence of the lateral dams, the effluent that must be appropriately treated constitutes the only discharge. It is also possible to control the mass of water above the sediments, which is what regulates the advective transport of contaminants.

As regards the costs: those of the filling are lower than those of the CDF on land, those of the excavation are lower than those for the underwater CDF and also the monitoring is easier and cheap

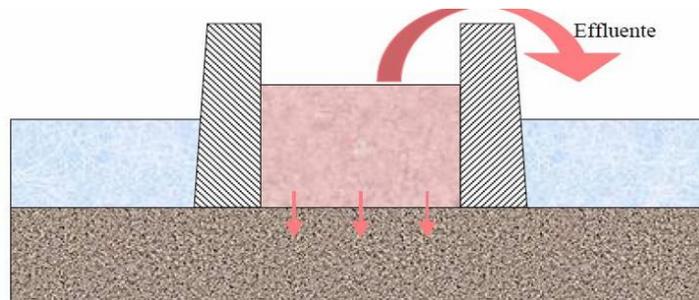


Figure 2.23 - Schematic of NICDF

### Underwater CDF (SCDF)

Being invisible makes this type of reclaimed basin more tolerated by public opinion, even if the lack of visibility can be a cause for abandonment of the work, furthermore, it does not cause limits to the navigability of the area; however, it is subject to erosion phenomena by marine currents. A great advantage of this type of CDF is that the stored sediments are always in anoxic conditions which ensure that heavy metals remain immobile, eliminating the risk of leaching; on the other hand, however, the upper surface in contact with the water constitutes a further route for the contaminants to escape and furthermore it is not possible to control the force of the water through the overlying water head, as was the case with NICDFs (Figure 2.25).

As regards costs, those related to excavation are undoubtedly higher than those of other types of CDF, while those related to filling and maintenance are lower. Being invisible makes this type of landfill basin more tolerated by public opinion, even if the lack of visibility can be a cause for abandonment of the work, furthermore, it does not cause limits to the navigability of the area; however, it is subject to erosion phenomena by sea currents.

A great advantage of this type of CDF is that the stored sediments are always in anoxic conditions which ensure that heavy metals remain immobile, eliminating the risk of leaching; on the other hand, however, the upper surface in contact with the water constitutes a further route for the contaminants to escape and furthermore it is not possible to control the force of the water through the overlying water head, as was the case with NICDFs.

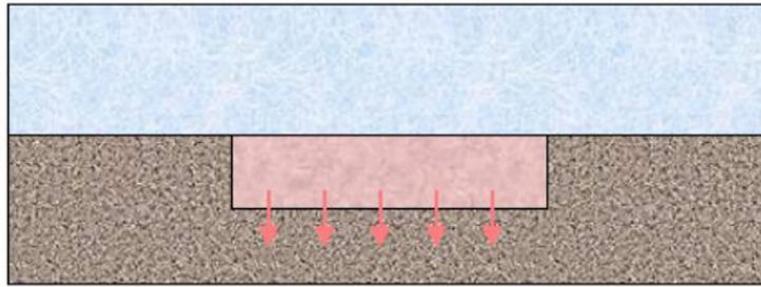


Figure 2.24 - Schematic of SCDF

When designing a reclaimed basin, it is important to take into account:

- quantity of material to be stored;
- dredging, transport and filling methods;
- physical properties of the sediments;
- contaminants present and their release potential.

To estimate the environmental impact of a CDF, it is necessary to evaluate the quality of the interstitial water of the sediments, the flows exiting the CDF and finally, after a certain time, through dispersion criteria, the volume of the area surrounding the CDF affected by the contamination to evaluate the use of containment measures.

The main containment measures consist of reducing the hydraulic head in order to prevent infiltration and advective transport; lining the bottom of the CDF with clayey material rich in organic matter; lining the bottom and walls of the CDF with a sandy layer with a high content of organic matter. The effluent from transport and/or pumping operations and that originating from the drying and consolidation of sediments in the CDF, presents contamination mainly in the form of suspended particles, therefore by using sedimentation basins or flocculation plants it is possible to significantly reduce the level of contamination.

The concentration of nutrients in the effluent must also be monitored, which come from contact with sand and clay with a high organic substance content and from prolonged stagnation in the reclaimed tank. It is necessary to reduce the concentration of nutrients in the effluent in order to avoid excessive consumption of oxygen in the surrounding waters, this is done in special nitrification plants.

The following figure illustrates the main escape routes of contaminants from a CDF (Figure 2.26).

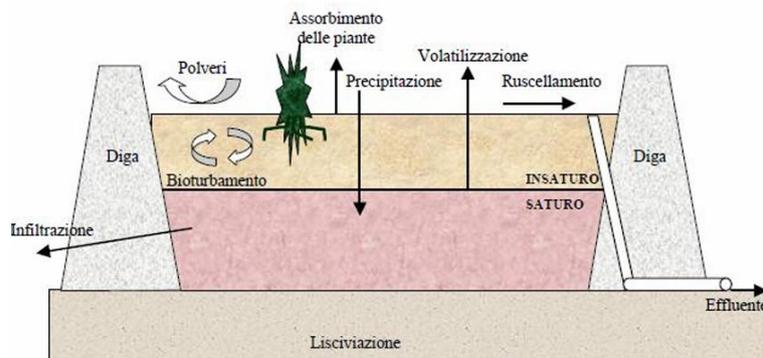


Figure 2.25 - Possible ways of material loss

When the dredged material is deposited in liquid form, the coarser fraction rapidly sinks near the discharge zone forming a slurry, while the finer fraction continues to circulate in the containment zone to settle more slowly. The clean water exits through an outlet structure. The rate of outflow, for continuous discharge operations, is approximately equal to the inflow rate: once the material consolidates, the pore water (possibly contaminated), is expelled.

Consolidation lasts for a long period after discharge, thus reducing the volume occupied. Unless prevented, the surface begins to dry out and, in relation to the adjacent water level; the deposited material may dry out across the entire vertical profile: the surface may crack and vegetate. The physical-chemical and bio-chemical behaviour of the tank is that as soon as the dredged material begins to dry and is therefore exposed to the atmosphere, oxidation begins: the initially dark water gradually becomes lighter as does the material. Oxidation and pH reduction, especially in marine sediments, and the resulting chemical transformations, can have a significant impact on the mobility of contaminants. If the sediment is rich in sulphur, organic matter, and poor in carbonates, oxidation can cause the formation of strongly acidic conditions: this increases the release of particulate metals into the interstitial water and the current. Unsaturated conditions of the dredged material across the entire vertical profile of the tank occur only when the infill tanks are built on land above the water table, while in an aquatic environment, most contaminants remain chemically immobile. The main elements that constitute the capital costs of a CDF are: design costs; land and expropriations; dam and contaminant control materials; construction equipment and labour costs.

## DREDGED MATERIAL AS A RESOURCE

Dredging and the dredged material itself, if of consistent quality, are essential for the maintenance and development of ports and waterways, for reclamation and flood management: all these activities involve the creation of large volumes of material, which can therefore become a valuable resource, even if much of it is not used due to economic, logistical, legislative or environmental constraints. Many countries have already moved towards an intensive use of this resource, such as Japan, where more than 90% of the material itself is used, in others there are many limits that prevent different uses: first of all the cost, generally higher than normal disposal methods, secondly the difficulty of finding suitable projects for the use of the material at the right time or adequate markets and finally the complex and inadequate legislation. Public opinion is often also negative. The possibilities of use can be classified mainly into two groups:

- Engineering use, for the production of building materials, insulation, flood defence and nourishment;
- Environmental use, such as the creation or improvement of habitats, the maintenance of places with sediment deficits or other.

Factors that need to be considered for the successful use of dredged material as a resource include:

- Communication - the imperative must be to gain trust from the public, regulators and wider stakeholders (Figure 2.27).



Figure 2.26 - Example of an explanatory panel positioned in the port area of Genoa, during the dredging works of 2008-2014, to communicate and explain the activities that were carried out in the Port (Cutroneo et al. 2014)

- Economics - taking into account cost savings for primary resources and making a proper assessment of costs and benefits for society;
- Legislation - it is important to ensure that national policies do not place dredged material unintentionally into waste legislation;
- Coordination - between supply and demand this is strategic and can be achieved at local, regional or basin scale;
- Technical and administrative - where planning and detailed site-specific solutions are needed;
- Environmental - where proper knowledge of natural processes is essential for adequate risk assessment and environmental improvements.

Traditional open water storage methods in dredged material management are often perceived as a source of risk for environmental resources. The main alternative in the past, especially for contaminated material, was to dispose of it in a Confined Disposal Facility (CDF), but in many areas these capacities became too expensive to build and raised many concerns about the environmental effects they produced. These structures progressively see their containment capacity reduced to critical levels, to the point where it is necessary to remove and treat the material inside to make room for the newly dredged material. In some places, raw materials are scarce and could be replaced by secondary materials such as dredged material. The classic management of dredged material usually involves the removal of sediment from a given channel, an activity that by its nature creates risks for the environmental context; in fact, it can alter the morph-dynamical and ecological structure of a given system, proving a potential effect, equal or even greater, than that due to open sea disposal. Thus, in considering the various possibilities, there is a need to take a holistic view of the system in which dredging takes place, so as to include the potential effects of a given management strategy in a broader perspective. In addition to sustainable disposal of the material, the range of uses has diversified enormously in recent years to include road construction, brownfield remediation, construction materials, habitat and landscape creation, but further uses can be achieved with preliminary treatment of the dredged materials.

### RELATIONSHIP BETWEEN MATERIAL SUPPLY AND DEMAND AND OTHER CHARACTERISTICS OF DREDGED SEDIMENTS

Dredged material can be used directly, as aggregate, converted into construction material (bricks), used for embankments, embankments or beaches, and used to satisfy the sand deficit in areas subject to erosion and to build new wetlands.

Its potential use depends on the type of material, how and where it was taken, its availability and its engineering and environmental characteristics. For this reason, it is very important that the sediment supply meets the need for interventions in the vicinity and that it occurs in the most appropriate time. Similarly, it may be necessary to modify the project so that it corresponds to the characteristics of the available supply. In Japan, for example, more than 90% of the dredged material is used: part of it, after the initial positioning on land, is subsequently used for other purposes (Figure 2.28). In contrast, in Europe (Figure 2.29), it is evident that less than 10% of the material is used directly, although these figures do not include sustainable regeneration in rivers and near coastal systems where the material could help offset the need for sediment.

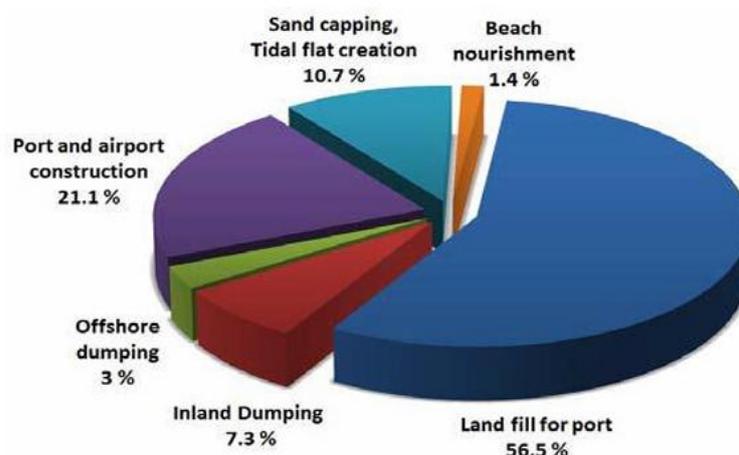


Figure 2.27 - Use of dredged material in Japan

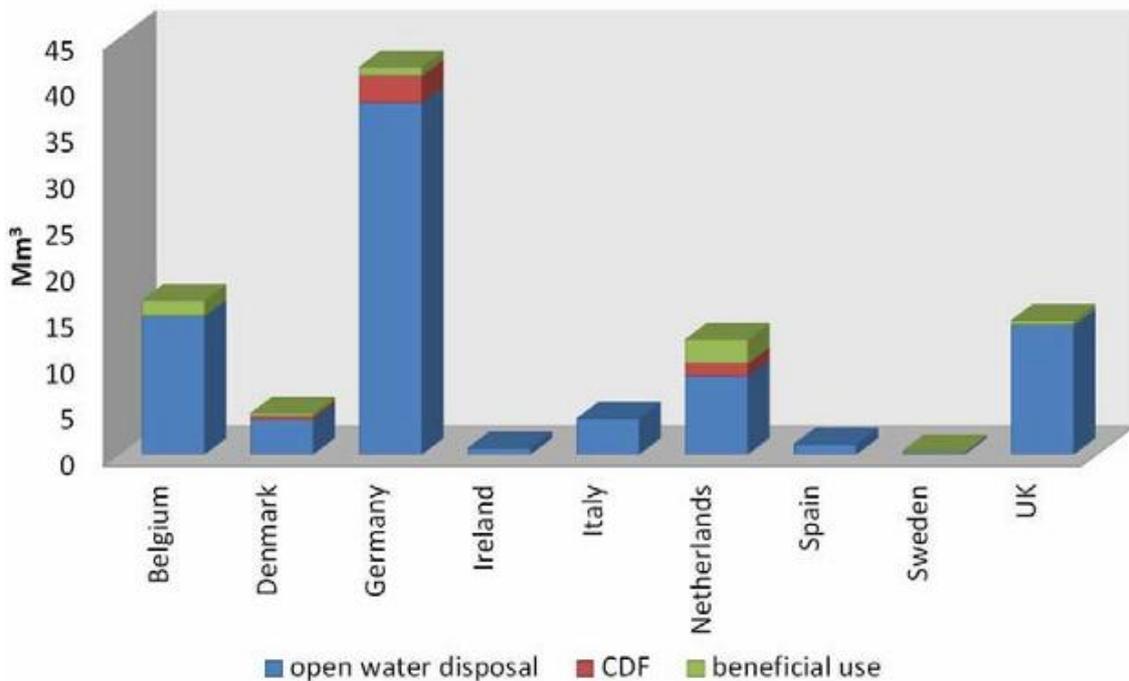


Figure 2.28 - Results of the CEDA questionnaire on the use of dredged material in Europe 2005

The quality and quantity of the material entrained are critical questions, along with the timing of the application: the timing of a maintenance or investment dredging project rarely coincides with that of the project and, even if they do, dredging can be controlled by environmentally dictated timing, to reduce the effects on the ecosystem.

Whether the dredged material can be used completely or not depends not only on the degree and type of contamination, but also on its physical characteristics, such as grain size, which largely determines the engineering and environmental uses of the material itself. The classification according to grain size includes five groups: rock, gravel and sand, consolidated clay, clay and silt and other mixtures.

- Rock - can be weak rock (sandstone or coral) or hard (granite and basalt); the fragments vary in size from small to large, depending on the dredging equipment used and on the material itself. It is usually not contaminated and can be used as a construction material and for interventions in aquatic or non-aquatic habitats.
- Gravel and sand - are generally considered the most versatile materials, requiring less treatment after dredging. Granular material can be used for nourishment, recreational parks and more.
- Consolidated clay - ranges from soft to hard and is usually obtained from investment dredging. If the water content is low, it can be used for brick making or in the construction of dams and embankments. - Clay/silt - is available after maintenance dredging of rivers, canals, estuaries and ports. The water content is usually high, so dewatering is necessary, which can last months or years depending on the drainage method and requires a large amount of storage space.
- Mixtures - are obtained from investment dredging and are due to glaciation processes, and include rock, sand, clay and silt. They can have a variety of uses such as filling and land improvement.

The most important criteria for matching the material to the intended use are the chemical composition and the grain size of what has been excavated. Environmental standards must be met for both engineering and environmental use of the material, but this does not categorically exclude contaminated sediments, as a certain level of contamination is considered acceptable, which depends on the type of use and the characteristics of the environment in which they will be placed.

## POSSIBLE ENGINEERING AND ENVIRONMENTAL USES OF DREDGED MATERIAL

### ➤ Building materials

The excavation of sand and gravel from ports or coastal areas for use as aggregate in building materials is a common practice: in some cases, the dredged material can be used directly with special excavation and transport techniques. For use on land, however, separation and treatment processes are often required to obtain concrete or other materials. Furthermore, the dredged material can be used as an alternative to some natural resources used in the construction industry: rock, sand, clay, various mixtures can become aggregates for concrete, components for bituminous mixtures, raw materials for the packaging of bricks or artificial boulders for coastal protection (cast dams). Appropriate analyses must confirm the suitability of the dredged material for the corresponding use as well as certify compliance with regulatory requirements. It is necessary to investigate what the chemical-physical properties are, and the most important parameters to observe are the degree of humidity, the grain size, the content of organic material and the type and concentration of pollutant.

### ➤ Coastal and flood protection

Coastal protection from erosion is a growing activity, due to a series of operations mainly due to human action, such as, for example, the increase in maritime construction, the blocking of longshore sediment circulation due to ports, the reduction of solid transport in rivers, the natural evolution of river mouths due to rising sea levels and the retreat of the coasts.

### ➤ Bank arrangements

Especially in the Netherlands, the arrangement of the banks of watercourses with the use of dredged material is a common operation: the dredged material, clean or slightly contaminated, can be deposited on the banks or on the embankments respecting some conditions, such as the fact that the quality of the soil on site must not worsen with the application of the material brought.

### ➤ Nourishment

Coastal protection involves artificially adding a given volume of sand through nourishment to stop or reduce the retreat of the shoreline caused by coastal erosion. The most significant environmental impact is because the organisms that live in that area are submerged. The fine sediments contained in the dredged material are first carried away by the current, favouring the formation of turbidity in the water before settling on the bottom, where the wave force is less. Normal TSHD dredgers pump the sand directly to the shore via pipelines. However, for dredging operations in small ports, usually done with the mechanical system, transport by barge finds a valid use. The unloading is carried out as close as possible to the beach at high tide, where the action of the waves transports the material and finally gives shape to the beach. To ensure that the sand actually reaches the beach, the hoppers must always be emptied to a depth below the so-called closing depth, i.e. within the active zone of the coastline. The creation of dunes behind the beach provides additional protection and allows the nourishment to last longer.

### ➤ Construction of embankments

Embankments must be strong enough to resist the actions of waves, in the case of maritime constructions, or to resist the current and the passage of boats, in the case of river embankments. Generally, gravel, rock or clay fills are used, which are preferred to sand.

### ➤ Construction of submerged barriers

They are made with different types of dredged material, parallel to the coast, although the orientation depends on the purposes of the project. There are three different types of submerged barriers:

- Fusible barriers: the purpose is to provide for the continuous deficit of sand in the active zone of the coast caused by erosion by the current and the waves;
- Protection barriers: designed to absorb part of the wave energy. This improves the recreational characteristics of the beach and, by inducing wave breaking, can favour surfing activity. In some

cases, the shape of these barriers is such as to realize the refraction of the wave, modifying the characteristics of the local solid transport;

- Containment barriers: used to isolate an area such as a site of deposition of contaminated material.

The grain size suitable for the construction of fusible barriers must preferably be medium or coarse, and they must be placed in shallow water, where the waves have a significant effect on the seabed, causing the transport of sediments. Protective barriers, on the other hand, are placed at greater depths, but always in such a way as to have control over the wave action. Containment barriers are suitable for those situations in which the particular shape of the seabed allows for the enclosing of a basin or quarry, where the material can be deposited and where the barrier acts as a dam to prevent the contained material from escaping. One of the advantages of this type of construction is the possibility of using self-propelled dredgers.

#### ➤ Construction of salt marshes

The dredged material, usually characterized by a fine grain size, can be used for the construction of salt marshes in tidal areas and exposed to erosion.

#### ➤ Creation and improvement of habitats

In this case the quality of the dredged material must be assessed not only on the basis of the requirements related to the intended use (grain size, total organic carbon, presence of various types of debris) but also on the basis of the nutrient content, the level of contamination, aesthetic and toxicological characteristics. The potential types of habitats that can be constructed vary from marshes and wetlands to bird nesting islands, underwater environments, fish farming improvement projects, biodiversity enhancement, etc.

#### ➤ Sustainable Landfill Operations

It consists of introducing dredged material into the marine environment to maintain or compensate for the deficit of sediments: this can be achieved either by deliberately deciding to drop the excess material during the loading operation of the dredged material or by placing the latter on the seabed. In any case, the normal hydrodynamic processes present in the area move the sediments.

### *RELATIONSHIP BETWEEN DREDGING METHODS AND MATERIAL USE*

In addition to considering how best to achieve the objectives of the dredging project, the intended use of the material should be considered in the choice of the best dredging and disposal technique; in this way, it becomes an integral part of the organizational strategy of the entire project. If the sediments do not directly correspond to the criteria of use, treatment processes will be necessary and, in this case, it will be necessary to connect the dredging process with the use process through an intermediate disposal phase. The need for treatment and the suitable type can have consequences on the dredging and disposal methods used. It outlines the operations that lead from dredging to the use of the material: it can be used directly without any intermediate phase (Direct use) or indirectly, as intermediate treatments are foreseen (Indirect use). Each type of use must respond to certain characteristics of the sediments and the water quality.

The criteria for choosing the most suitable path to follow can be divided as follows:

- environmental quality: the parameters to be assessed are chemical and biological. These criteria are valid for both an engineering use of the material and an environmental one;
- geotechnical quality: they include physical parameters such as granulometry, permeability, mechanical characteristics, etc.

#### ➤ Direct use

Investment dredging using suction dredgers with breaker, bucket dredgers, scoop dredgers or clamshell dredgers produces volumes of consolidated material, characterized by rock, sand and clay. It can be pumped via a floating pipeline to the reuse area or can be transported by barges to the designated area. The main uses are the construction of embankments, reclamation, offshore barriers and submerged barriers. Maintenance

dredging using suction dredgers provides material such as loose gravel, sand and mud; it is transported by the dredger to the use area but can also be deposited in the ship's hold via hatches and then pumped via a floating pipeline or pumped by jet.

➤ **Treatment phase**

For dredged material that does not meet the use criteria, numerous types of treatment have been developed. Physical techniques, such as dewatering and separation, are used to meet geotechnical requirements, while chemical, biological or thermal techniques are used to meet environmental requirements. However, if multiple requirements are imposed, a combination of techniques will be necessary, where the first phase is always dewatering, which suggests using systems that limit the water content in the material in dredging operations.

➤ **Intermediate storage**

For logistical reasons, it may be necessary to temporarily store the material; in direct use, this is primarily because dredging and use times do not coincide due to environmental and planning issues and then to the difference between the dredging production rate and the rate of use request. In the treatment process, however, intermediate storage may be required for a number of reasons, such as: the difference between the dredging capacity and that of the treatment, which is generally an order of magnitude lower than the former; create homogeneity in the input of the dredged material: certain treatments, such as mechanical separation, require homogeneous inflows for the success of the operation.

## APPLICABILITY OF SEDIMENT TREATMENT METHODS: BIBLIOGRAPHIC STATE

The intervention techniques for contaminated marine sediments are described in Legislative Decree 152/2006 and divided into two distinct categories: remediation operations and safety operations. Remediation operations concern the set of interventions aimed at eliminating the sources of pollution and pollutants or reducing the concentration to levels lower than the maximum levels established by the legislation. Therefore, allowing the recovery and restoration of the contaminated area.

On the contrary, safety operations are not aimed at removing pollutants but only at containing them to avoid their further spread in the environment. In general, these operations are applied as an emergency measure, in order to limit contamination while waiting for remediation operations, or as a definitive measure, when it is not possible to implement the remediation due to the lack of techniques suitable for removing pollutants, or because the remediation costs are unsustainable. It is therefore a limited solution, which should be used as little as possible and only when other working hypotheses have been discarded.

The classification system generally adopted to identify the type of intervention is that of the point of application of the same, for which there are interventions:

- **In-situ:** without movement or removal of materials from the site;
- **Ex-situ:** with movement and removal of materials from the site, in turn divided into interventions: On-site: with movement, removal of materials and treatment in plants specifically built within the area itself; Off-site: with movement, removal of materials and treatment in specific plants outside the area.

Another distinction between the many intervention techniques currently available can be made on the basis of their different operating principles and in general three macro technological areas can be identified relating to chemical-physical, biological and thermal processes (Table 2.7) (Reis et al., 2007).

Table 2.7 - Types of intervention for marine sediments.

<i>In Situ</i>	
	Monitored Natural Attenuation (MNA)
Bioremediation	Bioaugmentation
	Phytoremediation
	Biostimulation
Chemical Physical	Solidification/Stabilization
Containment measures	Sediment Capping
<i>Ex Situ</i>	
Chemical-Physical	Sediment Washing
	Chemical Oxidation
	Solidification/Stabilization
	Electrokinetic decontamination
	Solvent extraction
	Flotation extraction
Thermal	Thermal Desorption
	Pyrolysis
	Plasma
	Vitrification
	Incineration
	Steam extraction
Containment interventions	Bioslurry
	Biopile
	Composting
	Landfarming
	Phytoremediation
	MICP
	CDF
Dump	

It is necessary to clarify that among all the technologies and intervention methodologies applicable for contaminated marine sediments, there is no “universally best” solution, as each intervention is characterized by numerous site-specific factors taken into account in the characterization phase.

A global and general comparison can only be made for the functional choice based on the nature of the contaminants present and the physical characteristics of the sediment, as described in [Table 2.8 \(Perelo, 2010; Viviani and Di Bella, 2020\)](#).

In-situ interventions represent a good solution from both an ecological and economic point of view since, as previously mentioned, it is not necessary to remove the contaminated sediment from the site. At the same time, in the case of "sediments" and not "soils", these interventions represent very complex solutions due to the dynamic nature of aquatic systems and therefore to the possible release, mobilization and sedimentation of the pollutants present. Further disadvantages of in-situ techniques are also due to the difficulty of predicting the intervention times, controlling the process parameters and the possibility of formation of a secondary source.

**Table 2.8 - Functional choice based on the nature of the contaminants (in Italian; Viviani and Di Bella, 2020).**

Tecnica	Contaminante	Granulometria	Costo	Rendimento	Durata
Sediment washing	B - F	F - I	A - B	A	A
Solidificazione/stabilizzazione	C, E - F	A - I	A - B	A	B
Desorbimento termico	A - F, eccetto C	A - I	C - E	A	A - B
Landfarming	B - C	A - I	C - D	B	B - C
Biopile	A - D	C - I	E - F	A - B	A - B
Bioshurry	A - D	D - I	A - C	A	A
Phytoremediation	A - F	indipendente	D - E	C - D	D - E

Contaminante		Granulometria		Costo		Rendimento		Durata	
Tipologia	Classe	Tipologia	Classe	Range \$/m <sup>3</sup>	Classe	Range	Classe	Range	Classe
VOCs	A	Argilla fine	A	> 150	A	> 90 %	A	1 - 6 mesi	A
SVOCs	B	Argilla media	B	75 - 150	B	75 - 90 %	B	6 - 12 mesi	B
Idrocarburi da medi a pesanti	C	Argilla limosa	C	50 - 75	C	50 - 75 %	C	1 - 2 anni	C
Pesticidi	D	Limo argilloso	D	25 - 50	D	< 50 %	D	2 - 5 anni	D
Inorganici	E	Limo limoso	E	10 - 15	E			> 5 anni	E
Metalli	F	Limo	F	< 10	F				
		Argilla sabbiosa	G						
		Limo sabbioso	H						
		Sabbia	I						

As described in [Table 2.7](#), the in-situ intervention techniques, today really applicable for marine sediments, are some bioremediation technologies and "Sediment capping". The term bioremediation refers to in-situ treatment techniques that exploit the biological degradation process, using the metabolic potential of microorganisms to degrade a wide variety of organic compounds ([Scragg, 2005](#)).

Regarding these technologies (MNA, bioaugmentation, biostimulation and phytoremediation) there are numerous studies and applications at laboratory scale but few application experiences, which have highlighted a different behavior compared to experimental studies due to the numerous factors that come into play in real conditions. In this context, the maintenance of the long-term stationary process characteristics in full-scale plants is very uncertain.

On the other hand, "Sediment capping", although it presents advantages such as the reduction of the presence of pollutants in the water column and the reduction of their bioavailability for aquatic organisms, is an intervention that requires long-term monitoring and involves significant risks as the pollutants present in the sediments remain on the site ([Zeller and Cushing, 2005](#)). In particular, it is necessary to pay attention during the positioning of the covering material since the contaminated sediments could mix with the clean material and such positioning is particularly challenging in deep waters, with boat traffic (port areas) and wave action. The main risks are due to erosion of the cover and the diffusion of contaminants through the clean material. Furthermore, the preparation of the storage air is often laborious and equally expensive, if underwater storage (to be completed with possibly reactive capping) of large volumes of sediment is necessary.

As regards ex-situ interventions, the treatments that could be applied for the remediation of contaminated marine sediments in relation to the level and type of contamination are:

- Chemical-physical treatments: sediment washing, solvent extraction, flotation extraction, solidification/stabilization, oxidation, electrokinetic decontamination;
- Thermal treatments: steam extraction, desorption, vitrification, incineration, plasma thermal destruction, pyrolysis;
- Biological treatments: landfarming, biopiles, composting, bioreactors and MICP (Microbial Induced Carbonate Precipitation).

Following treatment, depending on the residual concentration of the contaminants present, the sediments can be reused or sent to landfill.

To date, the most widely used treatment techniques for the decontamination of marine sediments concern chemical-physical treatments since biological techniques, as already discussed for in situ treatments, do not find great application on a real scale due to the variability of the treatment; while thermal treatments would require on the one hand very high costs and on the other the impossibility of being able to reuse the treated materials in the port area as described by the current legislation (Ministerial Decree 173/2016). Therefore, chemical-physical interventions are presented as one of the best alternatives for the remediation of contaminated marine sediments thanks to the compromise between low costs and management flexibility. Among the technologies currently available that present these characteristics and allow satisfying the management options required by the standard, the Sediment Washing technology appears to be one of the "readiest" for the full-scale treatment of contaminated sediments, guaranteeing management flexibility and application to different territorial contexts. Specifically, Sediment Washing is an ex-situ remediation technique that originates from the already consolidated Soil Washing technology, in which the dredged material is subjected to a washing treatment with water or with specific extracting agents, in order to create favorable conditions for the mobilization of pollutants from the solid matrix (sediment)

## HYDRODYNAMIC CHARACTERIZATION OF PORTS

### GENOA PORT DYNAMICS

During the feasibility phase of the project to construct the new breakwater at the Port of Genoa, the Port Authority of Genoa (AdSP-MLO) carried out a detailed study of the dynamics of the water masses within the port (winds, currents and wave motion) (AdSP-MLO, 2020). The hydrodynamic circulation forced by anemometric conditions depends on the action exerted by the wind on large portions of the sea surface. Coastal winds come mainly from the first quadrant, while secondary winds come from the second quadrant (Figura 2.30).

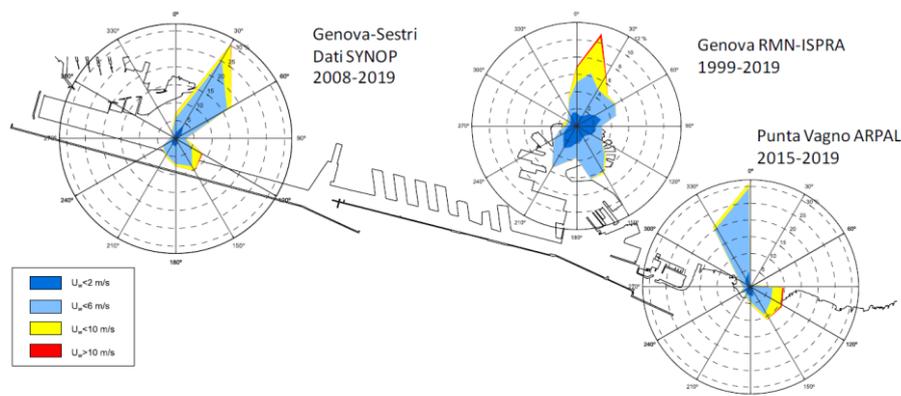
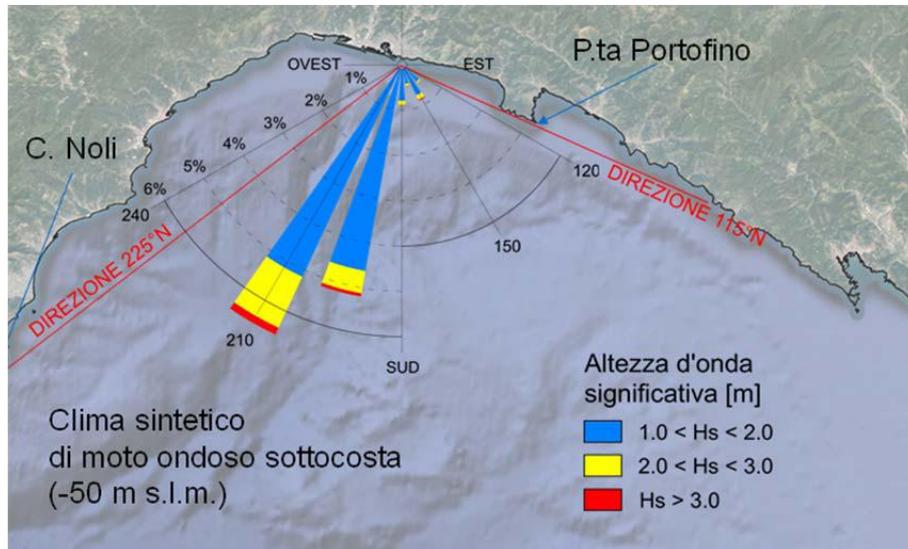


Figure 2.29 - The directional distribution of measurements observed at the anemometric stations of Genova-Sestri, Genova National Tide Gauge Network-ISPRA and Genoa Punta Vagno (AdSP-MLO, 2020)

Analyses conducted on historical wave motion data reconstructed by the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa off the coast of Genoa, for the period from 1979 to 2018, have made it possible to define the wave motion climate that characterizes the Genoa area.

For incident wave conditions, reference was made to the wave climate reconstructed as part of the Marine-weather Study for a point located off the Port of Genoa at a depth of -50.0 m above sea level, to which reference should be made for details. [Figura 2.31](#) shows the directional distribution of sea states with significant wave height  $H_s > 1.0$  m.



**Figure 2.30** - Figure Directional distribution of sea states with significant wave height  $H_s > 1.0$  m out of the Port of Genoa (AdSP-MLO, 2020)

The most frequent sea conditions outside the Port of Genoa occur in the Libeccio (SW) crossing sector (approximately 29%), generally with wave heights between 0.5 and 3.5 m. Furthermore, the Libeccio sector, with the highest wave heights, which can reach values of approximately 5 m annually, is the prevailing sector for the area under consideration. Sea conditions originating from the Scirocco (SE) are less frequent (5-6%) with wave heights generally ranging between 0.5 and 2.0 m, with maximum annual values between 3.0 and 3.5 m.

The total energy of the wave motion that acts on the coastline on average, which is the main cause of potential sediment transport along the coast, can be represented by a synthetic wave (equivalent climate wave) characterized by a direction of origin of 199°N, i.e. coming from the SSW, with a wave height of 2.0 m and a persistence of approximately 25 days per year.

The current configuration of the external works of the Port of Genoa guarantees a high level of protection of the port water surface from incident wave motion, so much so that, from this point of view, the port can rightly be considered a “port of refuge”, particularly in relation to storm surges coming from the SW (180-240°N).

The port is more vulnerable to Scirocco sea conditions (120-135°N), when waves penetrate through the eastern entrance, affecting the outer port and the Calata Oli Minerali. Scirocco sea conditions also penetrate the port through the western entrance, affecting the water near the mouth of the Polcevera river.

The results of the simulations conducted also showed that the surface current is obviously stronger and then weakens at depth.

SCENARIO: SCIROCCO (SE). Inside the port, the Scirocco wind helps to generate a current that flows within the Sampierdarena Basin, with speeds ranging from 10 to 20  $\text{cm s}^{-1}$ , which increases in intensity in the Airport Channel with values of around 30  $\text{cm s}^{-1}$ .

Detailed are reported in [Figure 2.32-2.35](#).

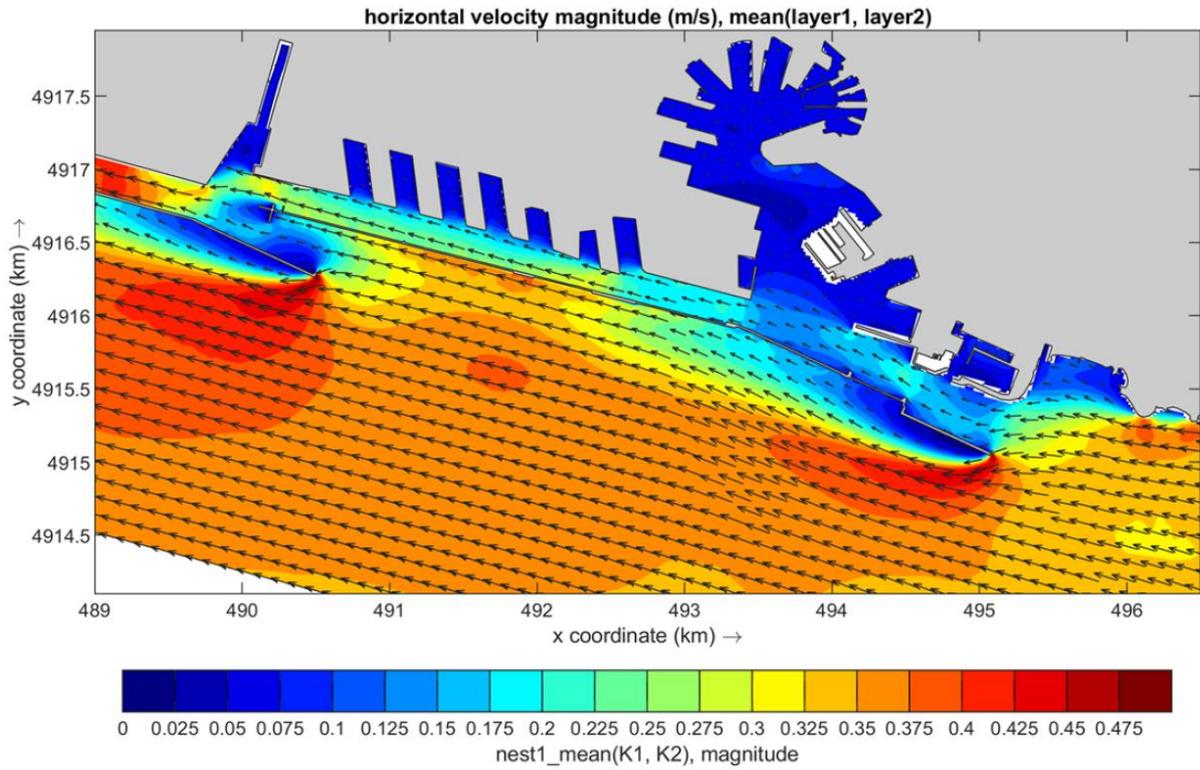


Figure 2.31 - Figure Current field in the surface layer in the presence of Scirocco wind (AdSP-MLO, 2020)

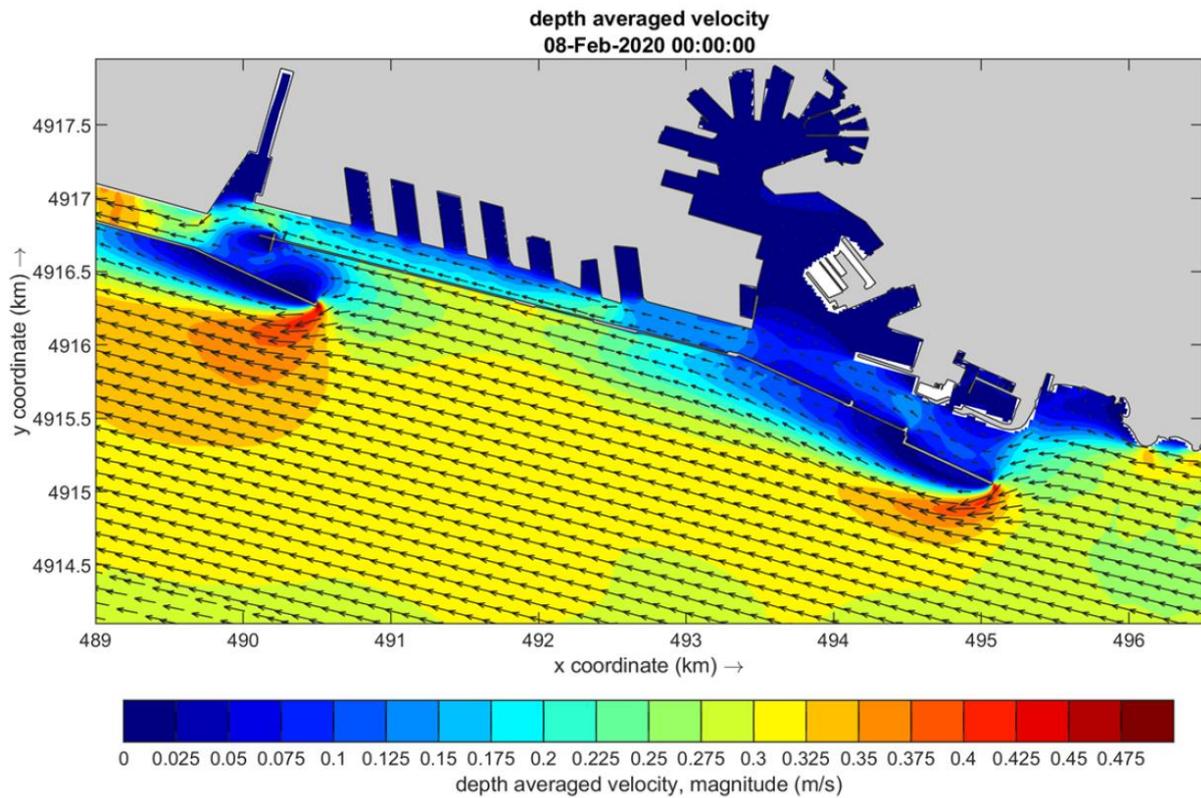


Figure 2.32 - Figure Current field in the water column in the presence of Scirocco wind (AdSP-MLO, 2020)

SCENARIO: LIBECCIO-MEZZOGIORNO (SW-S). The Libeccio/Mezzogiorno wind generates currents that are less intense than those generated by the Scirocco wind. Within the Sampierdarena basin, a weak current is generated, directed towards Levante, with maximum speeds of between 5 and 15 cm s<sup>-1</sup>.

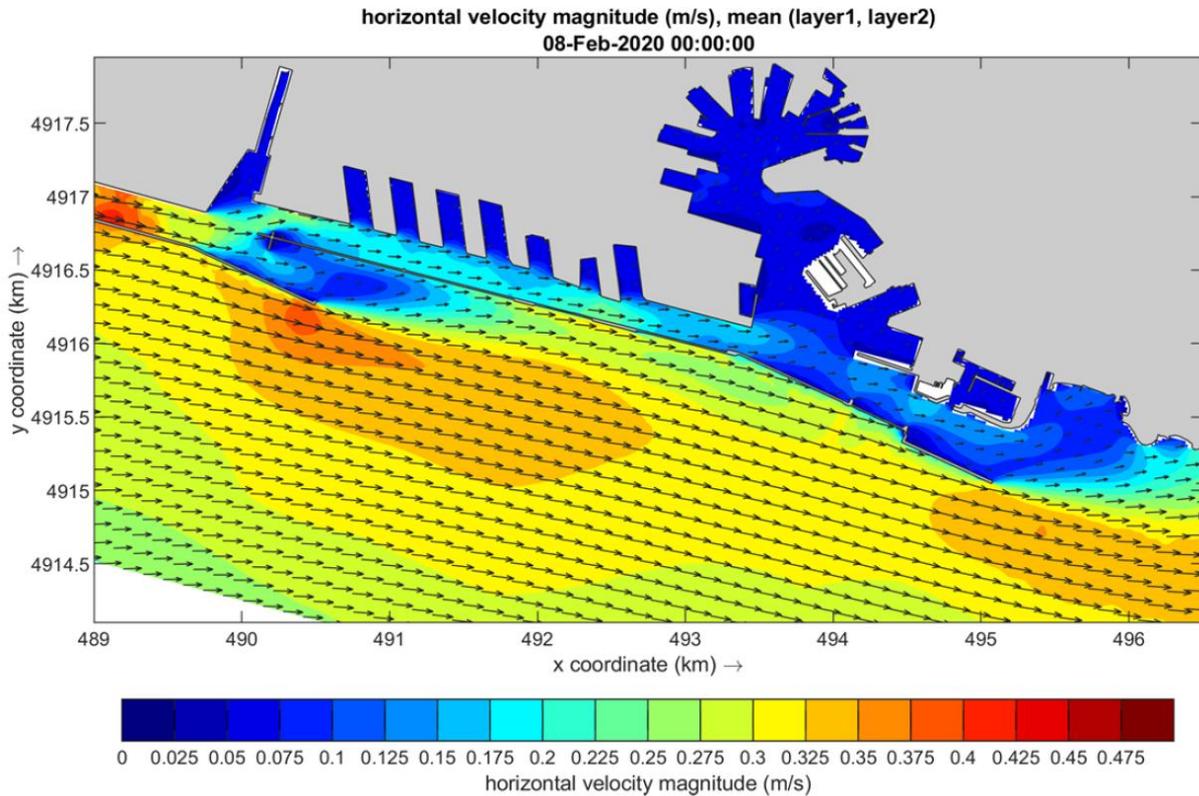


Figure 2.33 - Figure Current field in the surface layer in the presence of Libeccio/Mezzogiorno wind (AdSP-MLO, 2020)

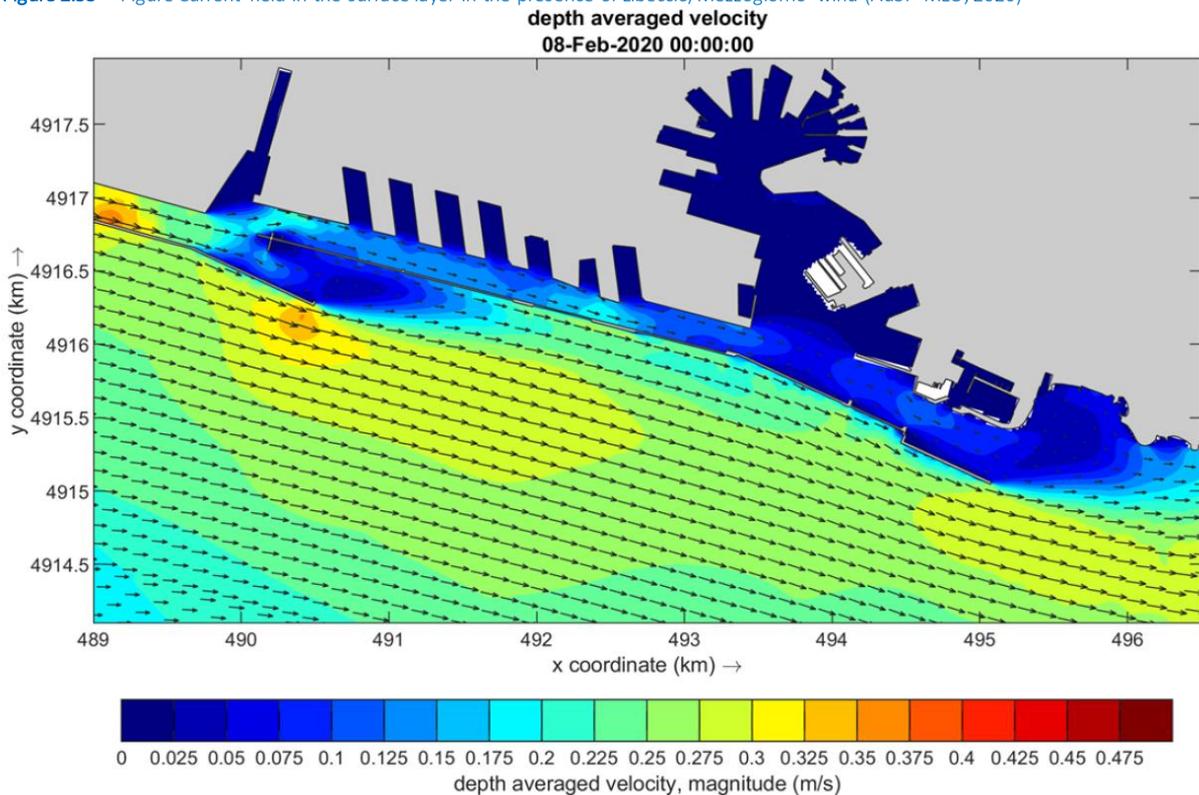


Figure 2.34 - Figure Current field in the water column in the presence of Libeccio/Mezzogiorno wind (AdSP-MLO, 2020)

## MICROFUNGI CHARACTERIZATION OF PORTS

### *MICROFUNGI IN COMMERCIAL PORT AND IN THE PORT OF GENOA: THE SEDITERRA PROJECT*

The characterization of fungal flora and the selection of species most suitable for mycoremediation allow the exploitation of microfungi naturally present within the matrix to be treated, such as bottom sediment, so as not to introduce alien species, also with a view to being able to use this type of treatment directly in the environment. The protocol for characterizing fungal flora and the criteria for selecting the most suitable species for mycoremediation were addressed in the SEDITERRA project as part of the INTERREG Italy-France Maritime 2014-2020 program ([SEDITERRA, 2019](#)).

The fungal strains were isolated from sediments in the various ports involved in the project: Genoa, Olbia, Livorno, and Pisa (the Navicelli Canal) in Italy, and Centuri and Toulon in France. Once all the species found had been correctly identified, those most suitable for mycoremediation tests for each sediment were selected, based on isolation frequency and bibliographic knowledge, both for organic and inorganic contaminants. Once the pools of species to be used had been identified, liquid inoculations of depleted culture medium (with reduced nutrient content) were made in order to promote fungal growth to the extent necessary for the fungi themselves in the sediment to be activated and stimulated to degrade and/or accumulate other substances.

The treatment was carried out *ex situ* in mesocosms, both for the removal of metals and for the degradation of hydrocarbons from port sediments.

The mycoremediation tests showed that fungal treatment was more effective in accumulating heavy metals than in degrading organic contaminants. One of the main limitations of the experiments was that they were carried out with relatively low contamination levels: both metals and organic contaminants were below the standard tolerance levels. The contamination actually worked on can be defined as residual. However, at least as far as metals are concerned, the results were very encouraging and promising.

In most sediments, there was a reduction in contaminants in the sediment and an increase in metal concentration on felt membranes inoculated with native fungi. As these are living organisms, a certain degree of selectivity emerged in metal accumulation: in fact, fungal species are able to absorb certain metals better than others, and not all have evolved the ability to bioaccumulate. There are, in fact, so-called metals with a biological function that fungi can absorb because they are crucial for ensuring proper cell function (e.g. Fe and Zn), while there are also indifferent metals that only some species are able to chelate and absorb thanks to the evolution of specific mechanisms and also thanks to adaptation and/or exposure to these metals themselves (e.g. Cr, As, Pb, Hg).

The use of native fungi was decisive in the selection of fungal strains, as they are undoubtedly the most suited to living in and tolerating the contaminated environment under study. On the other hand, there is a possibility that fungi may adopt exclusion as a survival strategy against a specific contaminant. This means that each species is skilled and very efficient at accumulating certain metals, while completely excluding others.

[Table 2.9](#) lists the native fungal species selected for each sediment for the treatment of both metals and organic contaminants. For mycoremediation treatment, the selection took into account not only bibliographic data, but also the number of colonies isolated for each species and their potential pathogenicity to humans and/or other organisms.

Table 2.9 - Fungal species selected for each treated sediment (SEDITERRA, 2019)

Sito di Campionamento	Specie fungine selezionate per il trattamento dei metalli	Specie fungine selezionate per il trattamento dei contaminanti organici
Genova	<i>Penicillium expansum</i> Link <i>Paecilomyces formosus</i> Sakag., May. Inoue & Tada ex Houbraken & Samson	<i>Neocosmospora solani</i> (Mart.) L. Lombard & Crous <i>Talaromyces amestolkiae</i> N. Yilmaz, Houbraken, Frisvad & Samson <i>Pseudallescheira boydii</i> (Shear) McGinnis, A.A. Padhye & Ajello <i>Paecilomyces formosus</i>
Livorno	<i>Penicillium brevicompactum</i> Dierckx <i>Mucor racemosus</i> Fresen	<i>Emericellopsis maritima</i> Beliakova <i>Epicoccum nigrum</i> Link
Pisa	<i>Cunninghamella elegans</i> Lendn. <i>Penicillium citrinum</i> Thom	<i>Trichoderma koningii</i> Oudem. <i>Penicillium camponotum</i> Visagie, David Clark & Seifert
Cagliari	<i>Fusarium oxysporum</i> Schldl. <i>C. cladosporioides</i>	<i>Cladosporium cladosporioides</i> (Fresen.) G.A. de Vries <i>Mucor racemosus</i> Fresen.
Centuri	<i>Penicillium</i> sp. e <i>Mucor</i> sp.	-
Tolone	<i>Penicillium</i> sp. e <i>Mucor</i> sp.	-

## THIRD SECTION: METHODS

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### INPUT DATA

The technical observations and modeling applications were based on a fragment of embedded within the "virtual model" (called RETURNOPOLY) of the so-called "Proof of Concept" chosen. In particular, in order to involve the different interdisciplinary aspects, and embrace a significant sample of data to analyze, two Italian realities were chosen that represent the common example of port activities and consequent processes:

- Commercial port: inspired by the port of Genoa (Liguria)
- Industrial port: inspired by the Port of Augusta (Sicily)

In fact, **task 4.5.3** of RETURN proposes only analyses and results concerning the port area of the "virtual model: RETURNOPOLY". In general, the port(s) included in the "Proof of concept" – concern the Key-classification/typology: commercial and industrial Harbor Area.

#### COMMERCIAL PORT: INSPIRED BY THE PORT OF GENOA (LIGURIA)

The economic development of the city of Genoa has been intrinsically linked to its harbor since its early foundations in the 6<sup>th</sup> century BC. The initial settlement grew around the Old Pier promontory. After the year 1000, with the revival of trade, Genoa developed into a significant city-port, a structure that remained largely unchanged until the mid-19<sup>th</sup> century. This port was situated between the natural harbor of Mandraccio Quay and the old Arsenal, backed by high, rocky shores.

Over the centuries, the port underwent various transformations and expansions to accommodate increasing maritime traffic and evolving needs. Key developments include the construction of new quays, dry docks, and the introduction of modern infrastructure like hydraulic cranes and railway connections reaching the quays. The late 19<sup>th</sup> and early 20<sup>th</sup> centuries saw significant expansion eastward and westward.

A pivotal moment was the renovation of the Old Port, designed by Renzo Piano, completed in 1992 for the Columbus Celebrations. This project reconnected the port area with the city, transforming it into a vibrant public space while preserving its historical significance.

In the following, the main peculiarities of the port Area are reported.

- Strategic Location: Situated in the most sheltered bay of the Ligurian Sea, Genoa's port holds a strategic geographical position in the Mediterranean, serving as a gateway to Southern Europe, North Africa, and the Far East. It is also a focal point of the EU Rhine-Alpine Core Network Corridor ([https://transport.ec.europa.eu/other-pages/transport-basic-page/rhine-alpine-core-network-corridor\\_en?prefLang=lv](https://transport.ec.europa.eu/other-pages/transport-basic-page/rhine-alpine-core-network-corridor_en?prefLang=lv)).
- Multi-Service Port: Genoa is a modern multi-service port equipped with a wide selection of specialized terminals. It can handle all major commodity sectors, including containers, general cargo, breakbulk, perishable goods, steel, forest products, and liquid/dry bulk. It also caters to both cruise and ferry passenger traffic.
- Comprehensive Services: Beyond cargo handling, the port guarantees a full range of complementary services, including ship construction and refitting, customized telecommunications, and data processing, supported by a network of dedicated companies.
- Leading Italian Port: Genoa is one of the most important seaports in Italy and a major hub in the Mediterranean, competing with ports like Marseille and Barcelona.
- Integration with the City: Unlike some industrial ports, Genoa's port, particularly the Porto Antico (Old Port), has been successfully reintegrated into the urban fabric, offering cultural attractions, leisure activities, and public spaces alongside its commercial operations.

- **Ongoing Development:** The port is continuously evolving with significant infrastructure investment plans aimed at improving maritime, road, rail, and air accessibility, as well as enhancing the sustainability of port activities. Presently the Port System Authority of the Port of Genoa is carrying on the construction of the new breakwater to allow the entry and mooring maneuvers of latest generation ships (due to naval gigantism).

In summary, the Port of Genoa boasts a rich history deeply intertwined with the city's identity, a strategic Mediterranean location, and a modern, versatile infrastructure capable of handling diverse cargo and passenger needs, all while striving for greater integration and sustainability.

Regarding the management of dredged sediments, and the dredging operations themselves, the Port has been involved in numerous technical-social intervention actions and procedures.

Here are some recent news and updates regarding sediment management at the Port of Genoa:

- **Dredging Operations:** Dredging operations are ongoing in the Port of Genoa with the aim of maintaining and increasing the depth alongside the quays. This is crucial for ensuring safe access for larger vessels, including both cruise ships and cargo ships. Recent dredging efforts have focused on areas like the cruise terminal at Ponte dei Mille and the ferry terminal wharves. The dredged material is sometimes repurposed, for example, in the construction of the new breakwater.
- **New Breakwater Project:** The construction of Genoa's New Breakwater involves significant sediment management. Dredged material from the outer harbor is being used to fill the prefabricated caissons that form the new structure, aligning with circular economy principles. The project also includes seabed consolidation work.
- **Environmental Considerations:** The Port Authority of the Western Ligurian Sea is increasingly focused on sustainable practices. This includes monitoring and removing pollutants from seawater and developing best practices in waste management, including sediment. There is also a focus on the reuse of dredged sediments.
- **Impact of Naval Traffic:** Studies are being conducted on the impact of vessel propellers on sediment transport within the port, which can affect the bottom topography and require management.
- **Sediment as a Resource:** There is a broader perspective looking at port sediments not just as waste, but also as a potential resource, with research into biotechnologies for decontamination and potential reuse in various fields.

For more detailed and the most up-to-date information, you can refer to the websites of the “Autorità di Sistema Portuale del Mar Ligure Occidentale” (Port Authority of the Western Ligurian Sea, <https://www.portsofgenoa.com/en/>) and news articles related to the Port of Genoa.

### *INDUSTRIAL PORT: INSPIRED BY THE PORT OF AUGUSTA (SICILY)*

The Port of Augusta, situated on the eastern coast of Sicily, boasts a long and significant history, deeply linked to its strategic geographical position. The natural harbor of Augusta Bay has been recognized for its potential since antiquity.

Historically, the bay served as an important anchorage and saw various naval activities over the centuries. Its sheltered waters and strategic location in the central Mediterranean made it a valuable asset.

Significant development of the port complex occurred in the 1950s and 1960s with the establishment of petrochemical plants and other industrial activities. This transformed Augusta into a major industrial port, particularly for oil refining and related industries. The port also became an important military base for the Italian Navy.

In the following, the main peculiarities of the port Area are reported.

- **Largest Natural Harbor in the Lower Mediterranean:** Augusta Bay is the largest natural harbor in the southern Mediterranean, offering extensive sheltered waters.

- **Multi-Functional Port:** It serves as a significant commercial port (handling liquid and dry bulk, containers), a crucial industrial port (dominated by petrochemical activities), and an important military base. There are also areas dedicated to tourism and recreational boating.
- **Strategic Location:** Its central position in the Mediterranean makes it a key transit point for international shipping routes and part of the EU's TEN-T core transport network.
- **Deep Waters:** The port features significant water depths (ranging from 14 to 18 meters, with some areas up to 22 meters), allowing access for large vessels.
- **Major Oil Port:** Augusta is one of Italy's leading oil ports, handling a large volume of liquid bulk related to the nearby petrochemical complex, which meets a significant portion of Italy's national fuel needs.
- **Extensive Infrastructure:** The port has a large water surface area, numerous berths, long quays and piers, and extensive land areas equipped for various port activities, including shipbuilding and repair.
- **Three Main Sections:** The port area is divided into three main parts:
  - Porto Xifonio: The outer harbor.
  - Porto Megarese: The inner harbor.
  - Seno del Priolo: The area facing the oil refining plants.
- **Intermodal Connections:** Efforts are underway to improve the port's connectivity, including a planned railway link to the Syracuse-Catania line.

In essence, the Port of Augusta is characterized by its vast natural harbor, its crucial role in Italy's energy sector, its strategic Mediterranean location, and its blend of commercial, industrial, and military functions.

In fact, due to the intense activities and the numerous industries that "overlook" the Rada, the area is recognized as a "Contaminated Site of National Interest - SIN": consequently, the waters and sediments of the Rada have been (and are) the object of continuous investigation and control.

Unfortunately, specific real-time news and updates on the sediment management of the Port of Augusta are not readily available in a constantly updating news feed.

However, based on the information available, here is what we can infer and some related points:

- **Focus on Environmental Monitoring:** There have been activities focused on updating the analysis of marine sediments in Augusta Bay. This suggests an ongoing interest in understanding the current state of the seabed and potential contaminants.
- **Expansion and Dredging:** As the port undergoes expansion, including the construction of a new container quay terminal, some level of dredging and sediment management is typically required. News from March 2024 mentions the port expansion.
- **Environmental Considerations in Development:** Studies and tools are being developed to assess the environmental impact of port activities in Augusta, including the impact of dredging. This indicates an awareness of the environmental aspects of port development.
- **Potential for Contamination:** Given Augusta's history as a significant industrial port, environmental monitoring of sediments is likely important to identify and manage any potential contamination.

To get the most current updates, you would typically need to refer to official publications from the Port System Authority of the Eastern Sicilian Sea or local environmental agencies in Sicily.

## CLASSIFICATION AND AVERAGE CONCENTRATION OF POLLUTANTS

### GENOA PORT SEDIMENT CHARACTERIZATION

The first case study examined concerns the characterization of sediments of the Port of Genoa. The first data available refers to the project relating to the first capital dredging carried out within the port between 2009 and 2014. The characterization of the sediments was carried out by ICRAM (Central Institute for Scientific and Technological Research Applied to the Sea) (ICRAM, 2007). In detail, the Genoa Port Authority project included:

- dredging activities relating to the Sampierdarena and Porto Antico basins, together with the area from the eastern entrance to the Grazie basin, for a total of approximately 2,700,000 m<sup>3</sup> of sediment to be dredged;
- the construction of a reclamation basin at Calata Bettolo, intended for the transfer of that portion of dredged sediment with concentration values compatible with this intended use;
- the filling of the water areas near Calata Derna and Calata Bengasi, for constructing a quay.

As part of this program of activities, the Port Authority of Genoa has commissioned ICRAM to design the seabed characterization activities preparatory to the planned dredging and quay construction works.

For the marine areas of the Port of Genoa affected by dredging and quay construction projects, ICRAM has therefore drawn up a specific Characterization Plan, modulating the sampling strategy for each area subject to intervention according to the bathymetric heterogeneity of the seabed, the qualitative variability of the sediments, based on previous information, as well as the internal structural layout of the port. The characterization activities planned for marine sediments have been divided into two distinct phases (Phases I and II).

- Phase I involved the characterization of the entire western port area, in particular the Sampierdarena Channel with all its internal docks, except for the Bengasi Quay and the mouth of the Polcevera stream, by taking 199 sediment cores, varying in length between 0.50 m and 8.00 m (for the performance of chemical-physical analyses on a total number of 922 levels).
- Phase II involved the characterization of the entire eastern area and part of the Old Port, in particular the Scalo Marittimo, the turning basins, the eastern access channel and the Bengasi Quay, through the collection of 137 sediment cores, varying in length from 0.50 m to 8.50 m (for the performance of chemical-physical and eco-toxicological analyses on a total number of 521 levels).

The characterization data obtained from surveys carried out within the Port of Genoa were processed using various geostatistical techniques to obtain the spatial distributions of the various survey parameters. Areas characterized by a different sampling grid were treated separately to respect the different levels of information available during the estimation phase. The areas relating to the slipways and turning basins were discretized, for estimating the survey parameters, with three-dimensional grids with cells measuring 30x30x0.5, while the remaining areas were discretized with cells measuring 50x50x0.5.

The grids were then cut into areas affected by excavation, and therefore subject to characterization, identified in accordance with the bathymetry provided by the Port Authority (Figure 3.1). The calculations relating to the areas affected by quay construction work went down to a depth of 3 m. The calculations relating to the areas affected by excavation projects went down to the actual excavation depth, calculated by comparing the project elevations and the bathymetry provided by the Port Authority. In the area of the turning basin and the Old Port, core samples taken below a sedimentary cover encountered a rocky substrate above the planned excavation levels. In these areas, the deepest layers of the processing grid stop at the estimated level of the rocky substrate.

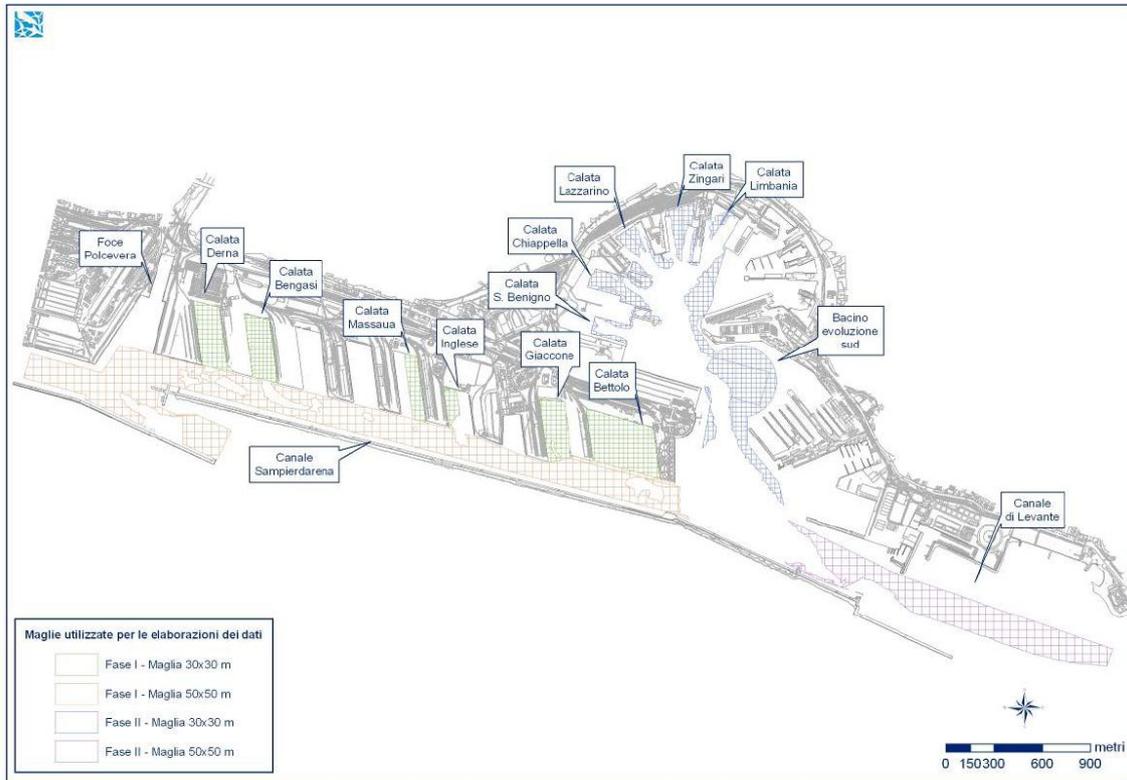


Figure 3.1 - Processing grid for the surface layer (ICRAM, 2007)

In general, all the areas characterized were found to be heavily contaminated; the pollutants identified (hydrocarbons, polychlorinated biphenyls, heavy metals and organotin compounds) are clearly linked to human activities. The highest levels of contamination were found in the turning basin and in the docks of the Old Port. Furthermore, where contamination was detected, it extends to the deepest levels. The results are shown, for each analyte, according to whether they exceed the concentration values reported in Tables 1/A and 1/B of Annex 5 to Part IV of D.L. No. 152/2006.

At the end of the assessments, ICRAM developed a geographical distribution of the concentrations, highlighting the areas of exceedance of each limit value with different colors. The identified areas are:

- **Purple Zone:** This color identifies the areas in which the exceeding of the classification limit values for dangerous substances has been found; in these areas, the highest level of contamination has been found.
- **Red Zone:** The areas in which the concentration detected are higher than the limit values of D.L. 152/2006 are represented in Red. In these areas there is the presence of health risk but the concentrations are lower than the classification limit values of dangerous substances.
- **Green Zone:** In these areas, the concentrations found were lower than the ICRAM intervention limit values.

The results for the compounds that showed the most significant concentrations (C>12 hydrocarbons, Pb for Phase I, and PAH sum and Hg for Phase II) are reported (Figure 3.2-3.25).

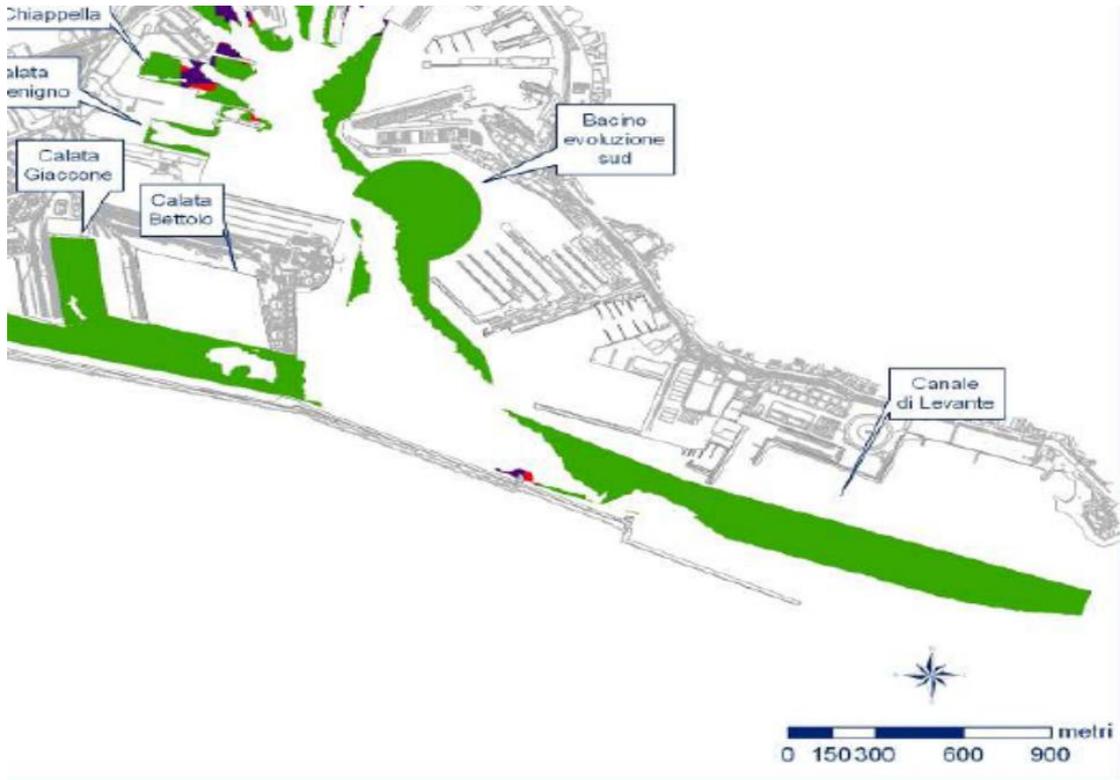


Figure 3.2 - Estimated concentration of C>12 hydrocarbons in the 0-50 cm layer (ICRAM, 2007)

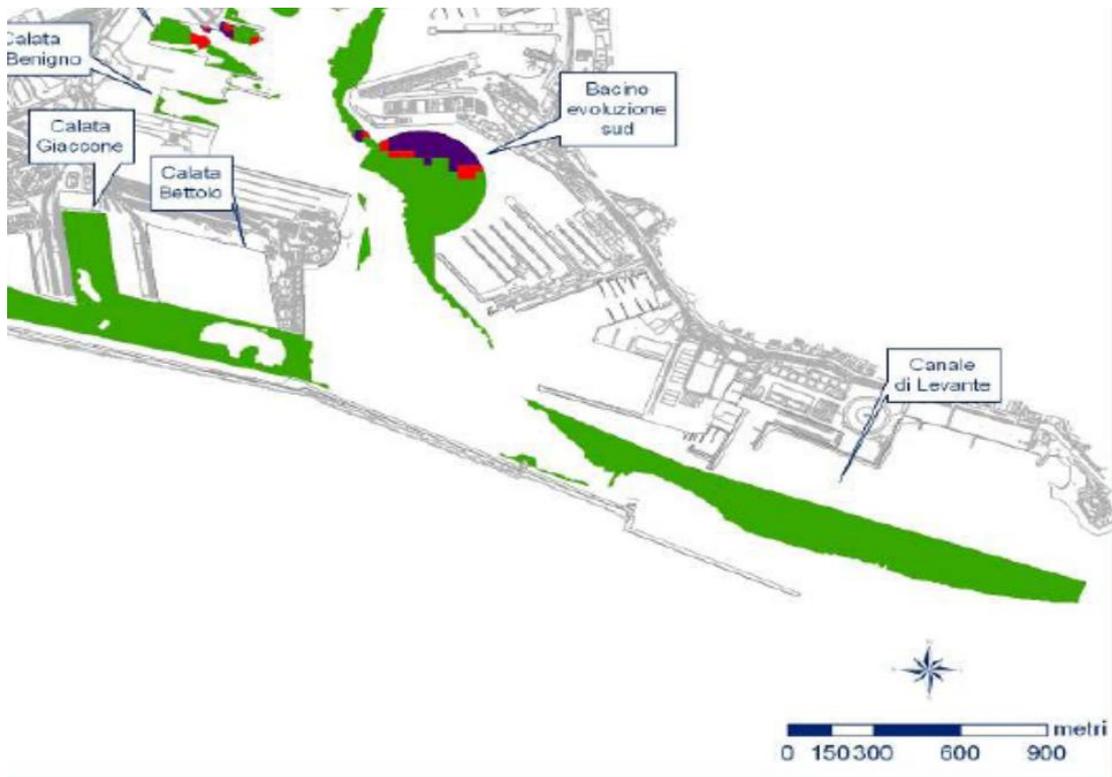


Figure 3.3 - Estimated concentration of C>12 hydrocarbons in the 50-100 cm layer (ICRAM, 2007)

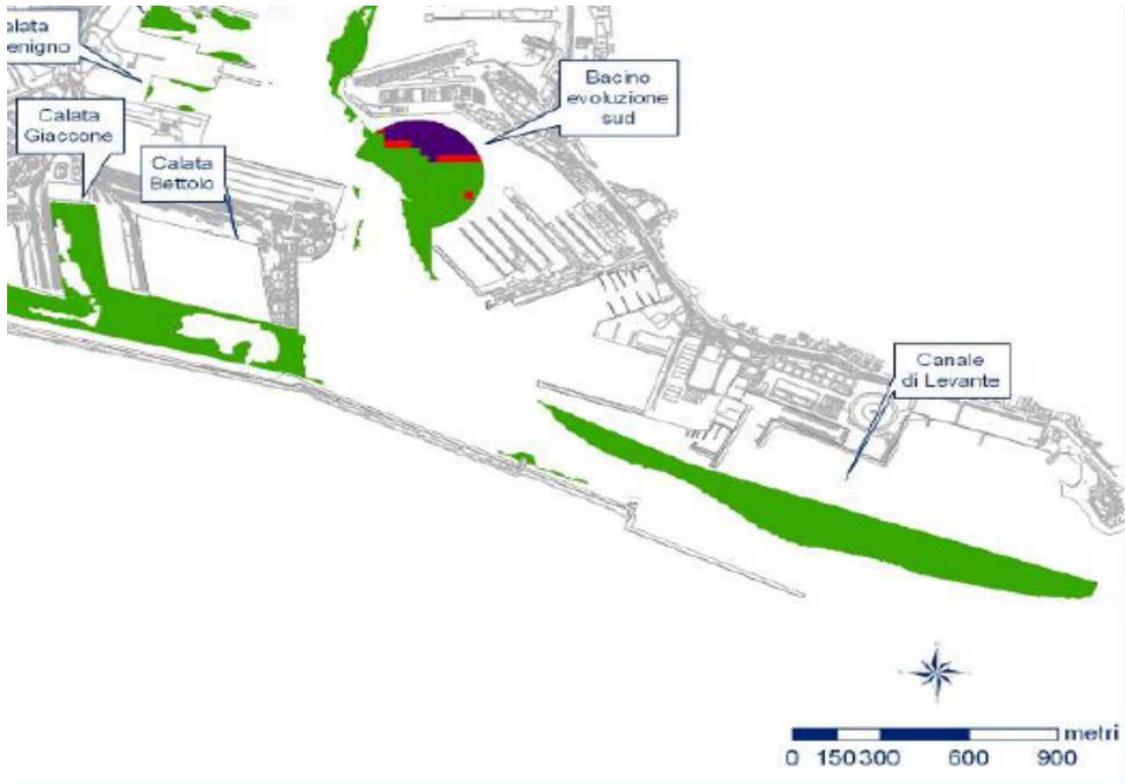


Figure 3.4 - Estimated concentration of C>12 hydrocarbons in the 100-150 cm layer (ICRAM, 2007)

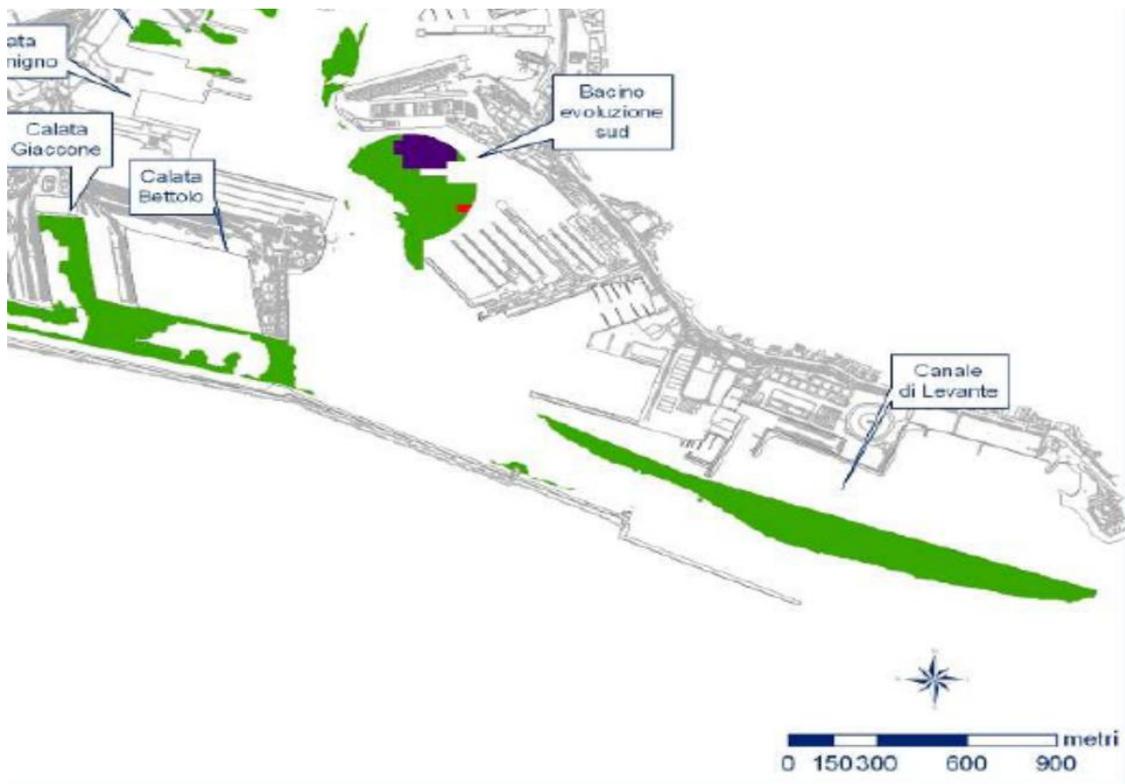


Figure 3.5 - Estimated concentration of C>12 hydrocarbons in the 150-200 cm layer (ICRAM, 2007)



Figure 3.6 - Estimated concentration of >12 hydrocarbons in the 200-250 cm layer (ICRAM, 2007)

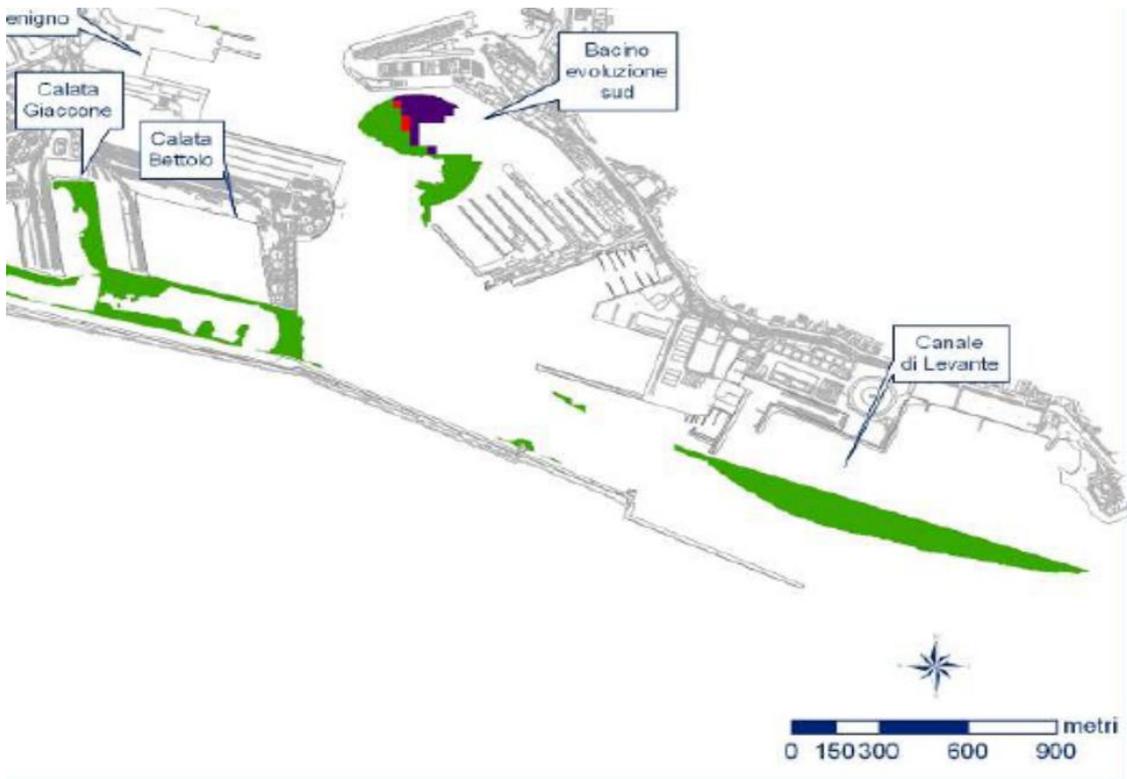


Figure 3.7 - Estimated concentration of >12 hydrocarbons in the 250-300 cm layer (ICRAM, 2007)

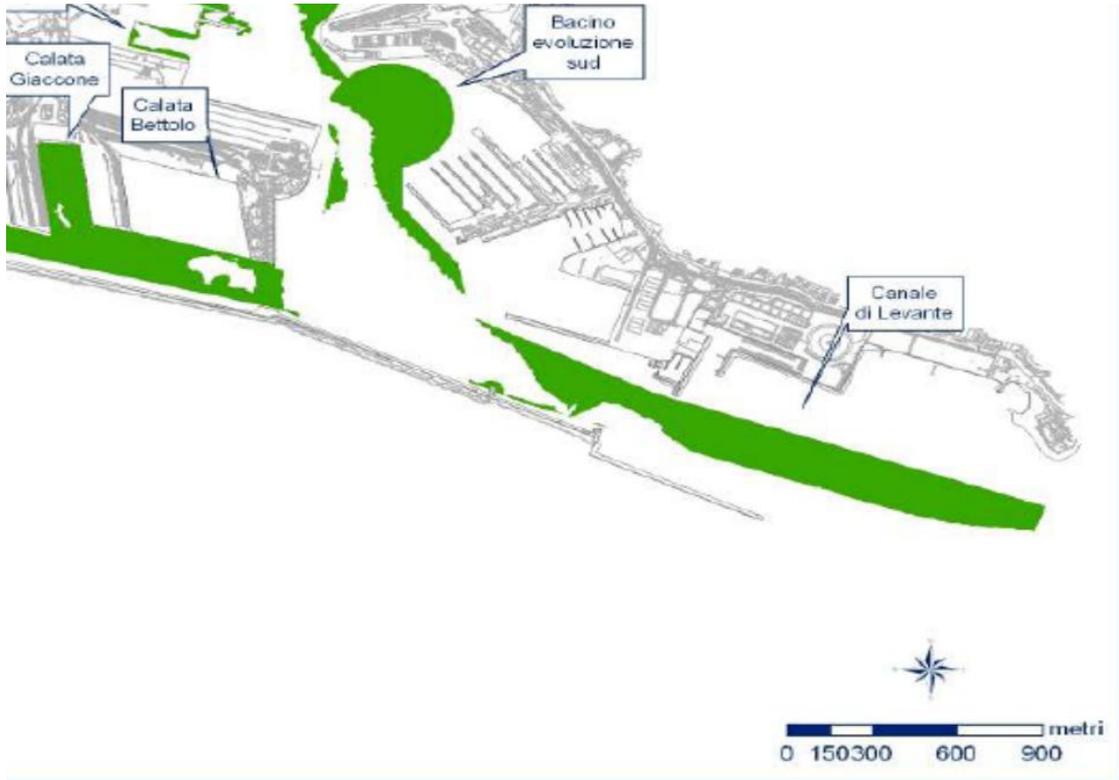


Figure 3.8 - Estimated concentration of Pb in the 0-50 cm layer (ICRAM, 2007)



Figure 3.9 - Estimated concentration of Pb in the 50-100 cm layer (ICRAM, 2007)



Figure 3.10 - Estimated concentration of Pb in the 100-150 cm layer (ICRAM, 2007)



Figure 3.11 - Estimated concentration of Pb in the 150-200 cm layer (ICRAM, 2007)

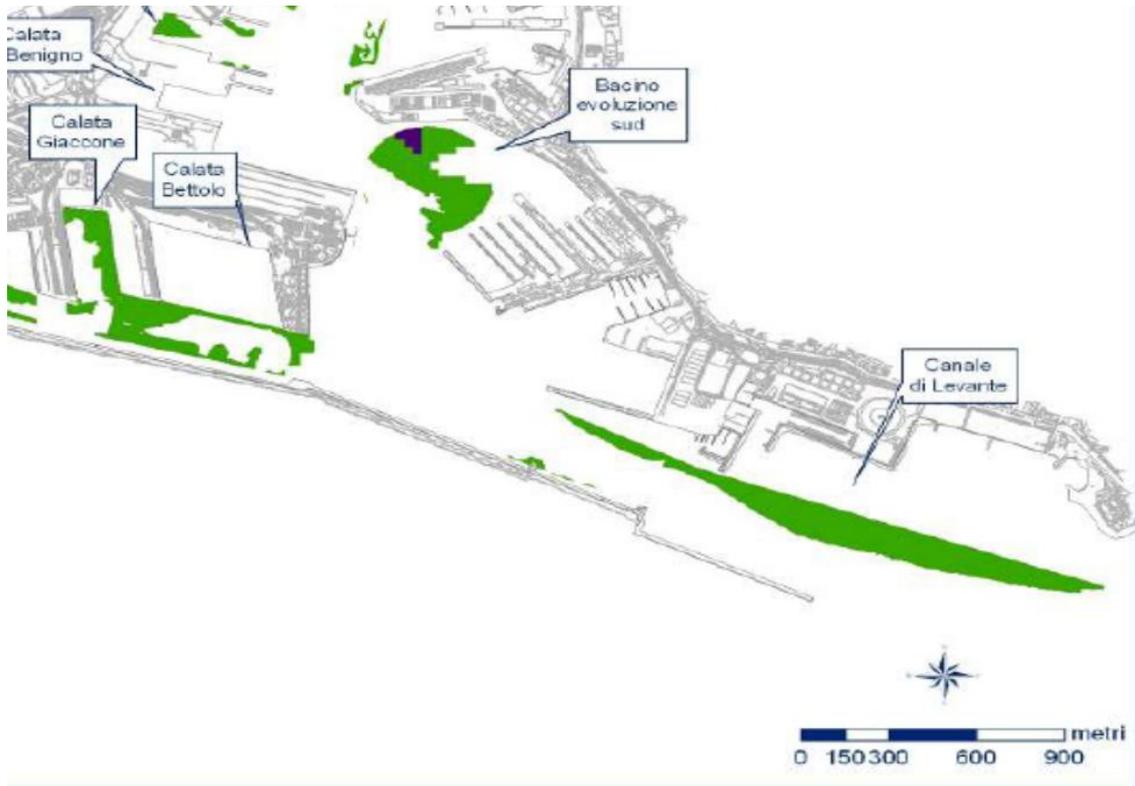


Figure 3.12 - Estimated concentration of Pb in the 200-250 cm layer (ICRAM, 2007)

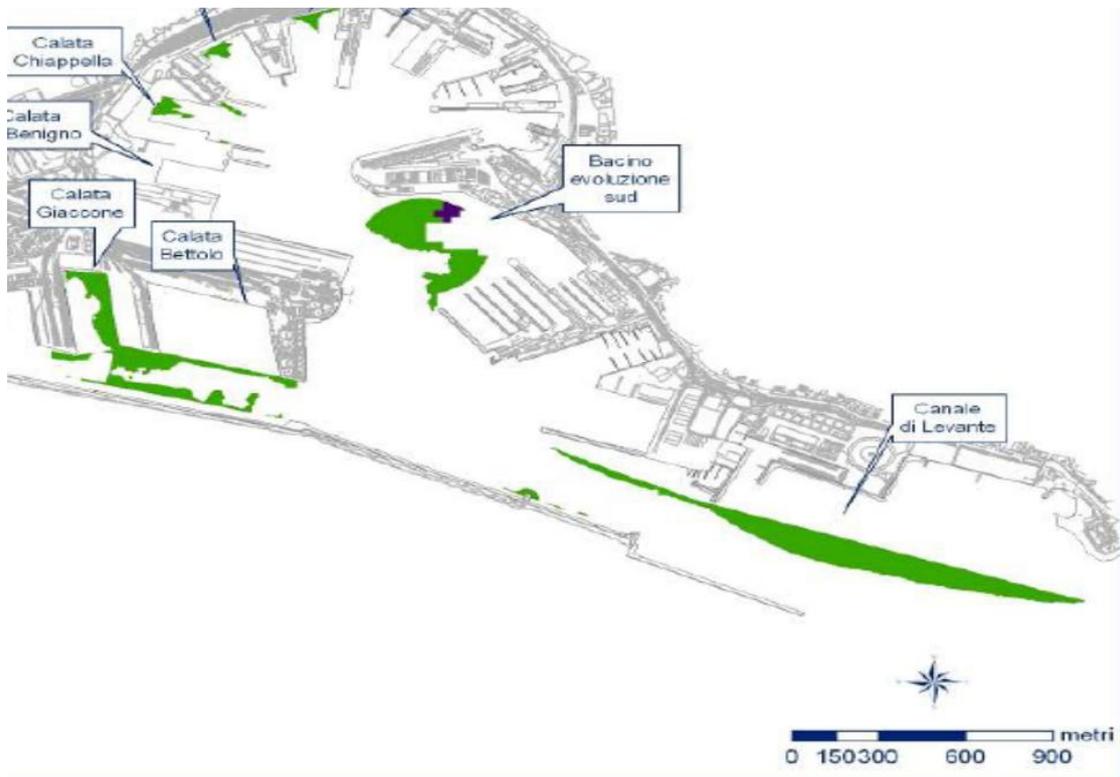


Figure 3.13 - Estimated concentration of Pb in the 250-300 cm layer (ICRAM, 2007)



Figure 3.14 - Estimated concentration of PAH sum in the 0-50 cm layer (ICRAM, 2007)



Figure 3.15 - Estimated concentration of PAH sum in the 50-100 cm layer (ICRAM, 2007)

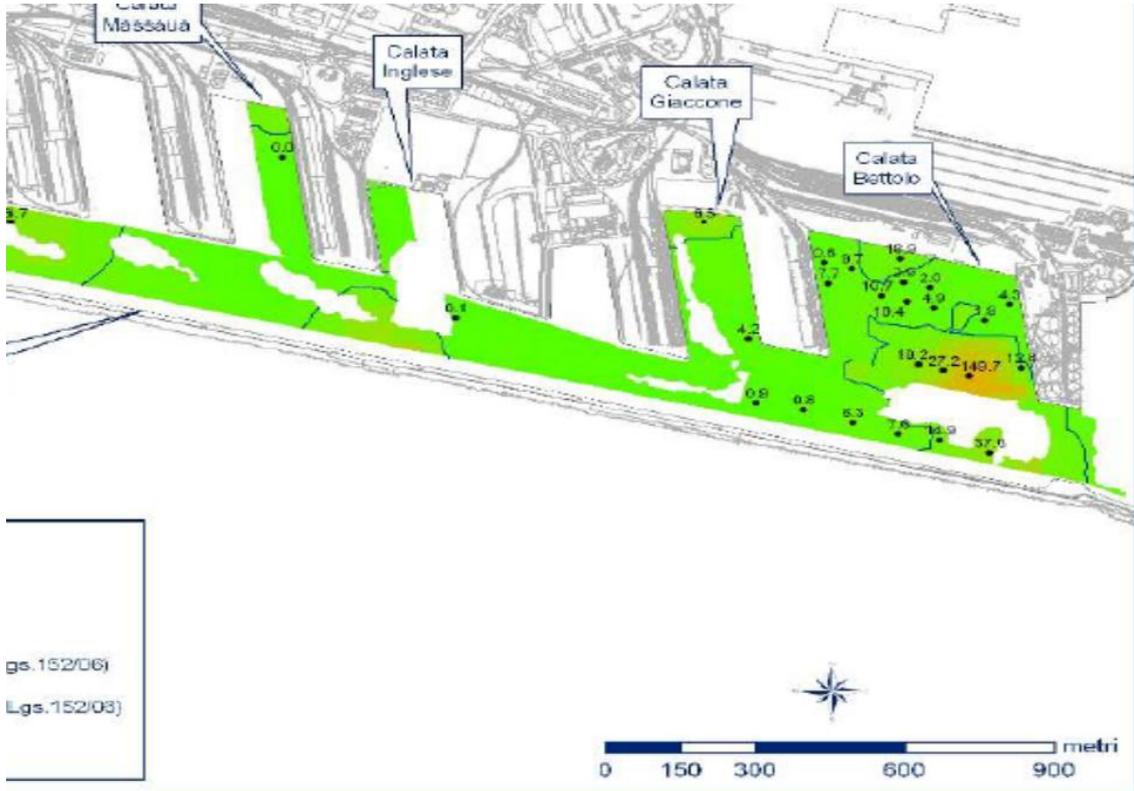


Figure 3.16 - Estimated concentration of PAH sum in the 100-150 cm layer (ICRAM, 2007)



Figure 3.17 - Estimated concentration of PAH sum in the 100-150 cm layer (ICRAM, 2007)

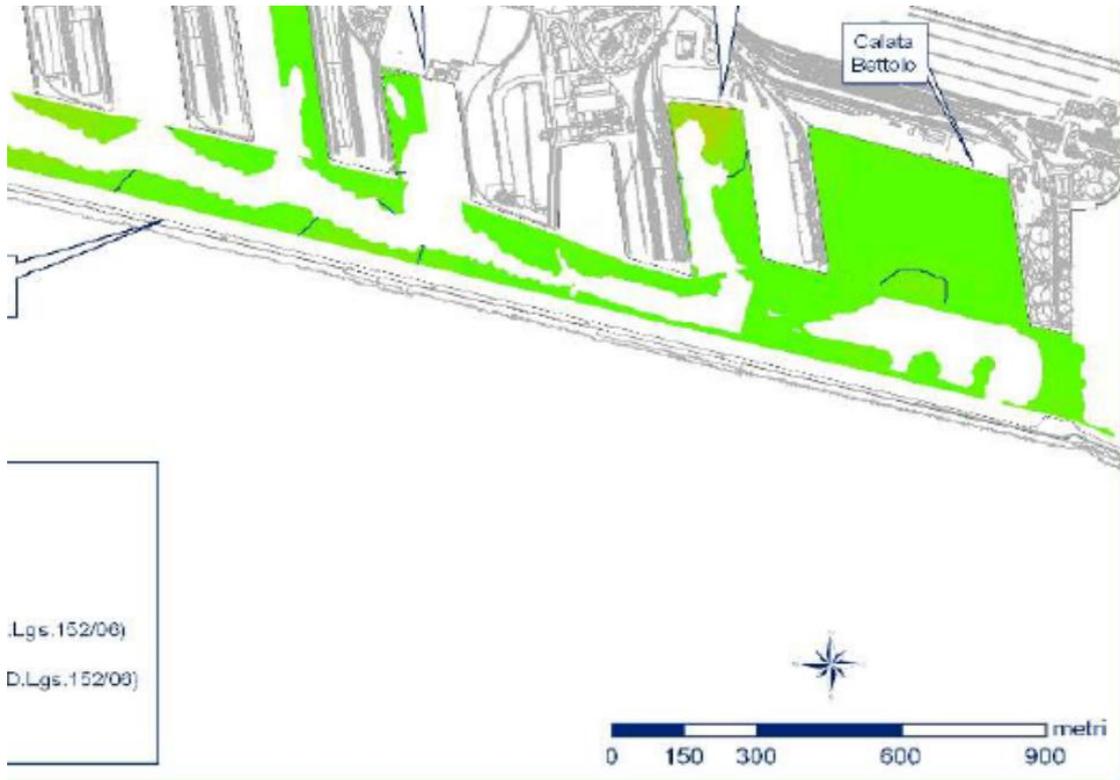


Figure 3.18 - Estimated concentration of PAH sum in the 200-250 cm layer (ICRAM, 2007)



Figure 3.19 - Estimated concentration of PAH sum in the 250-300 cm layer (ICRAM, 2007)

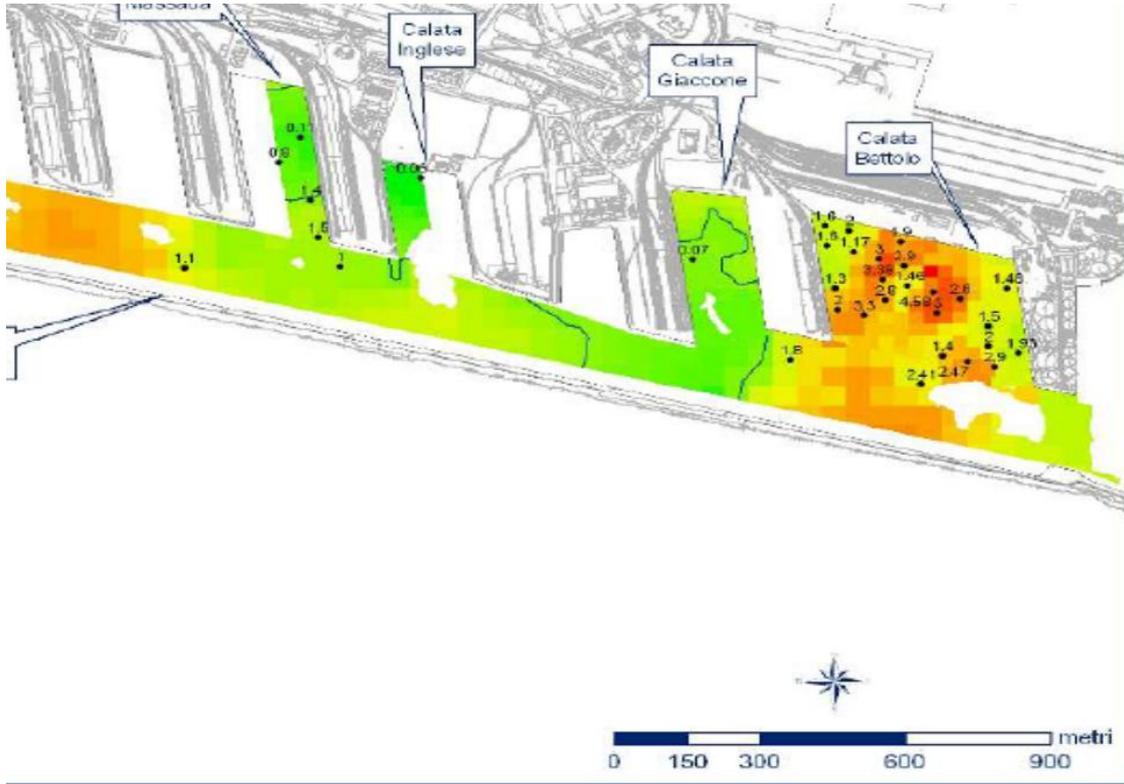


Figure 3.20 - Estimated concentration of Hg in the 0-50 cm layer (ICRAM, 2007)

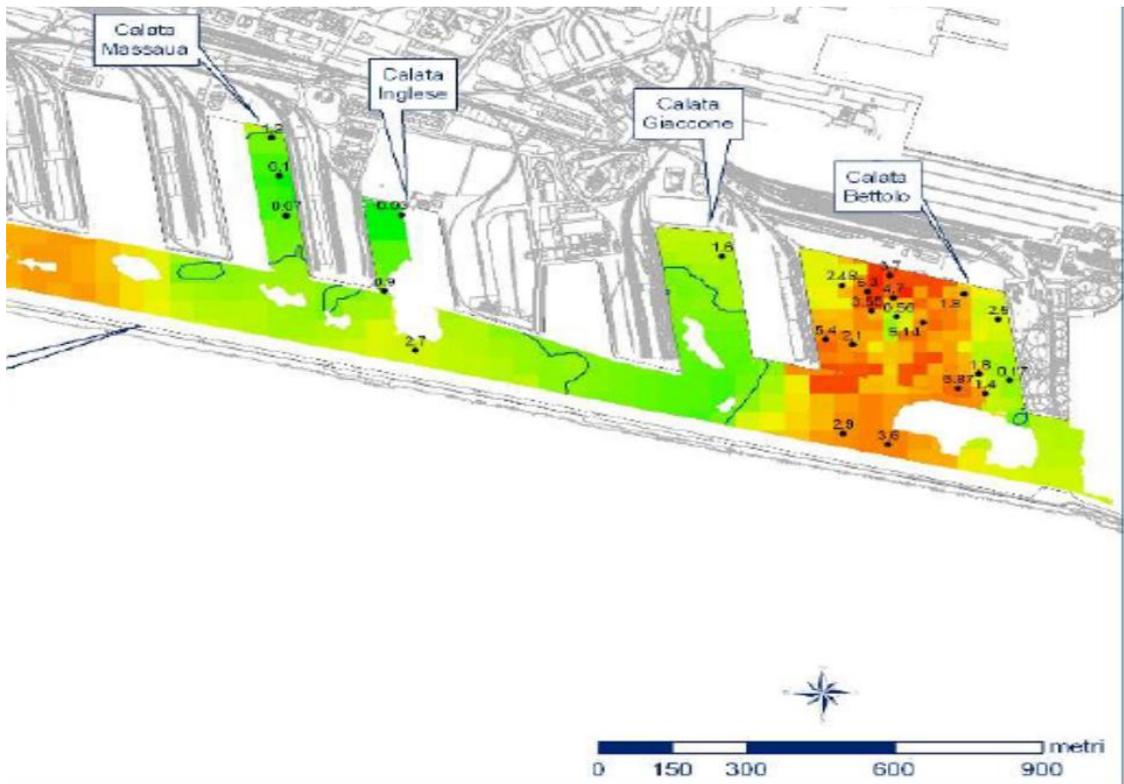


Figure 3.21 - Estimated concentration of Hg in the 50-100 cm layer (ICRAM, 2007)

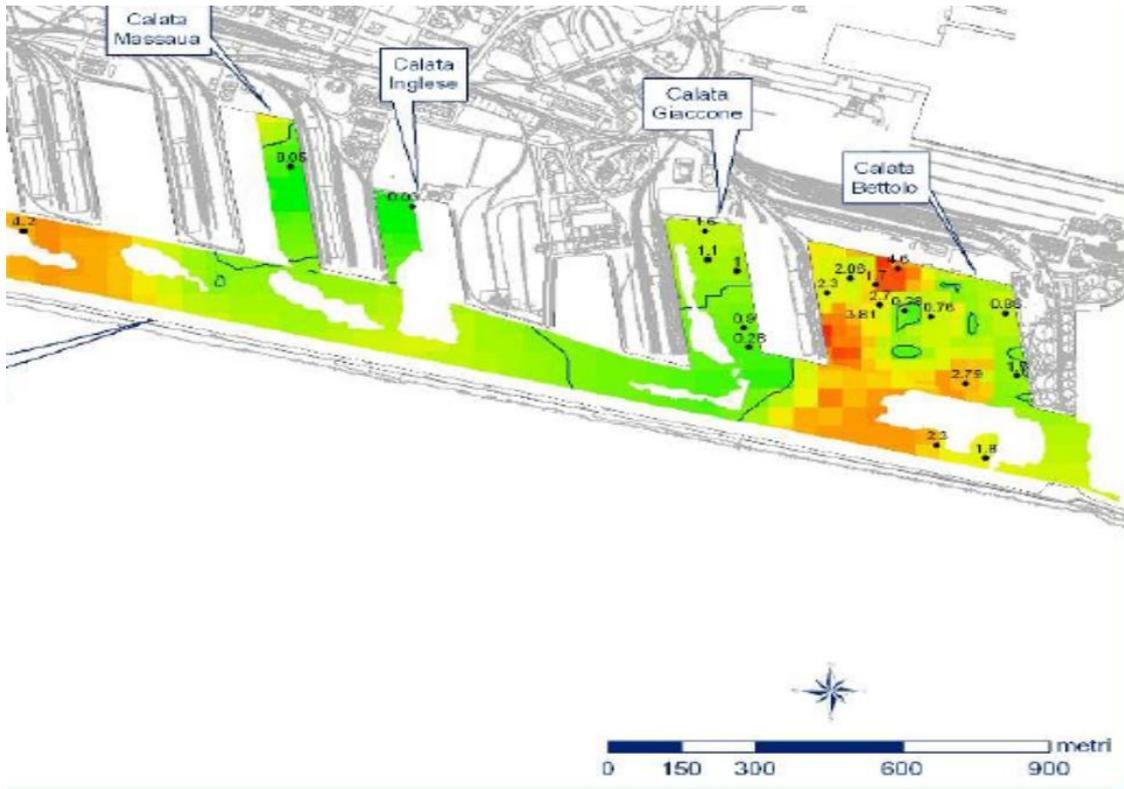


Figure 3.22 - Estimated concentration of Hg in the 100-150 cm layer (ICRAM, 2007)

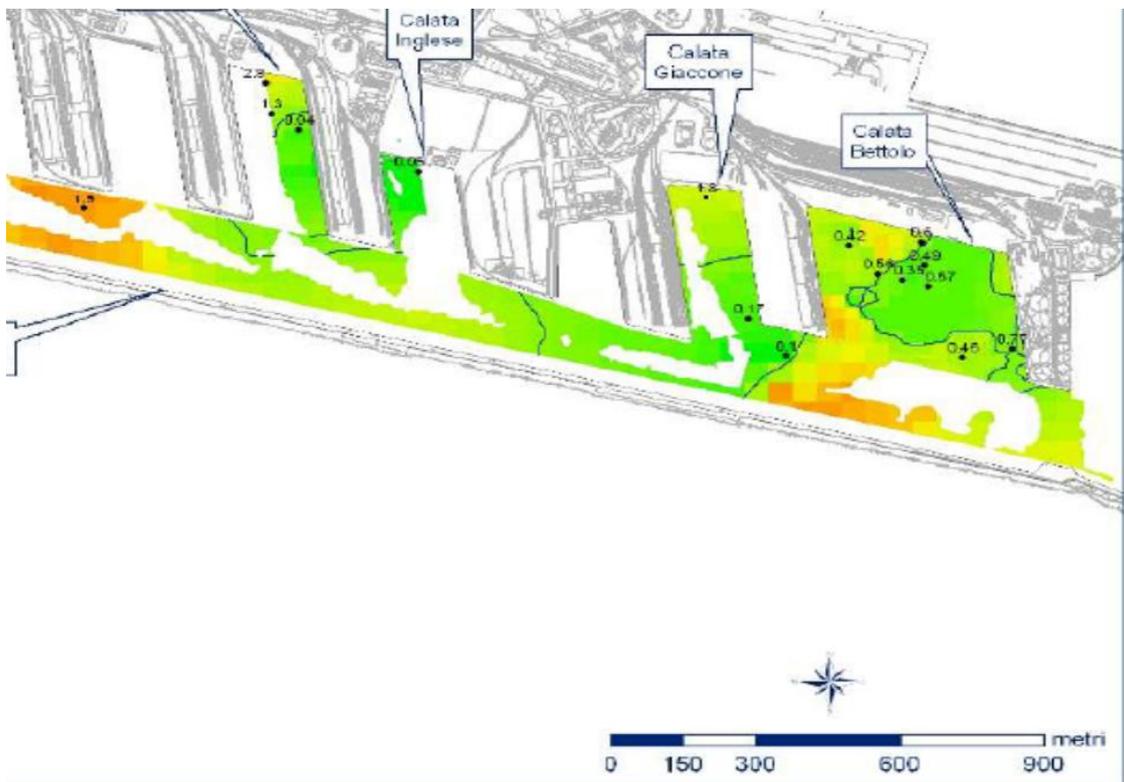


Figure 3.23 - Estimated concentration of Hg in the 150-200 cm layer (ICRAM, 2007)

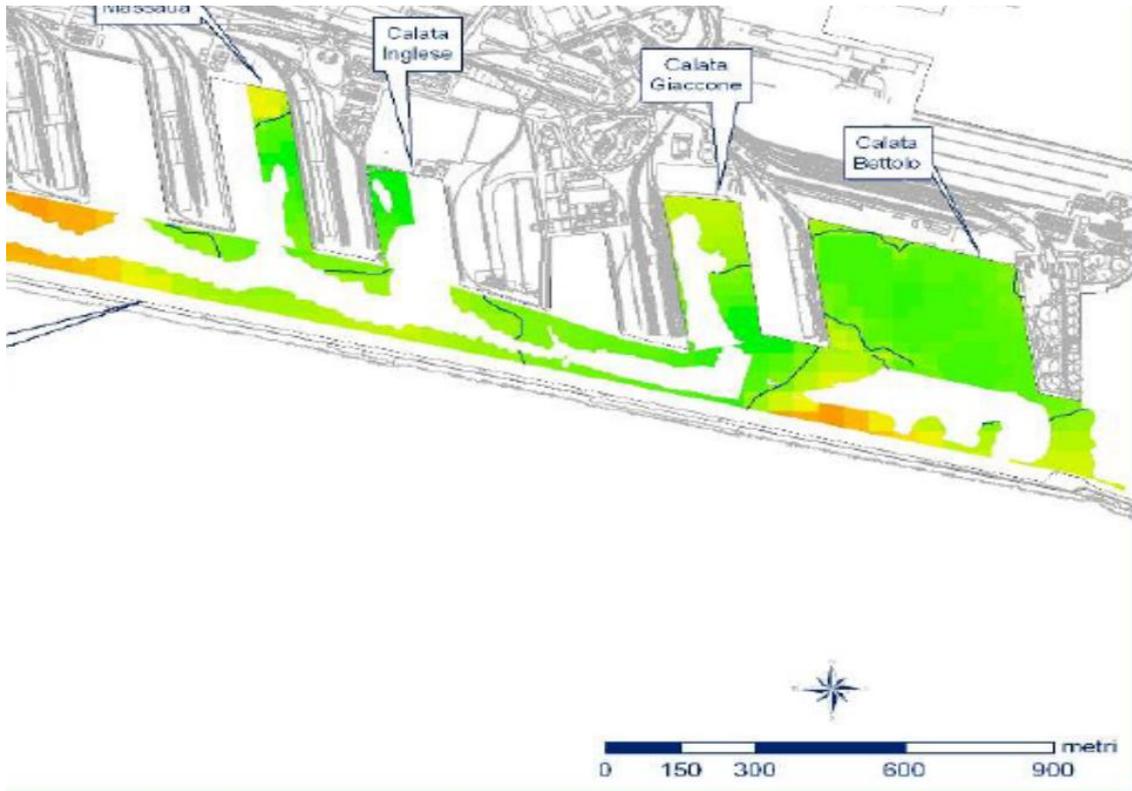


Figure 3.24 - Estimated concentration of Hg in the 200-250 cm layer (ICRAM, 2007)

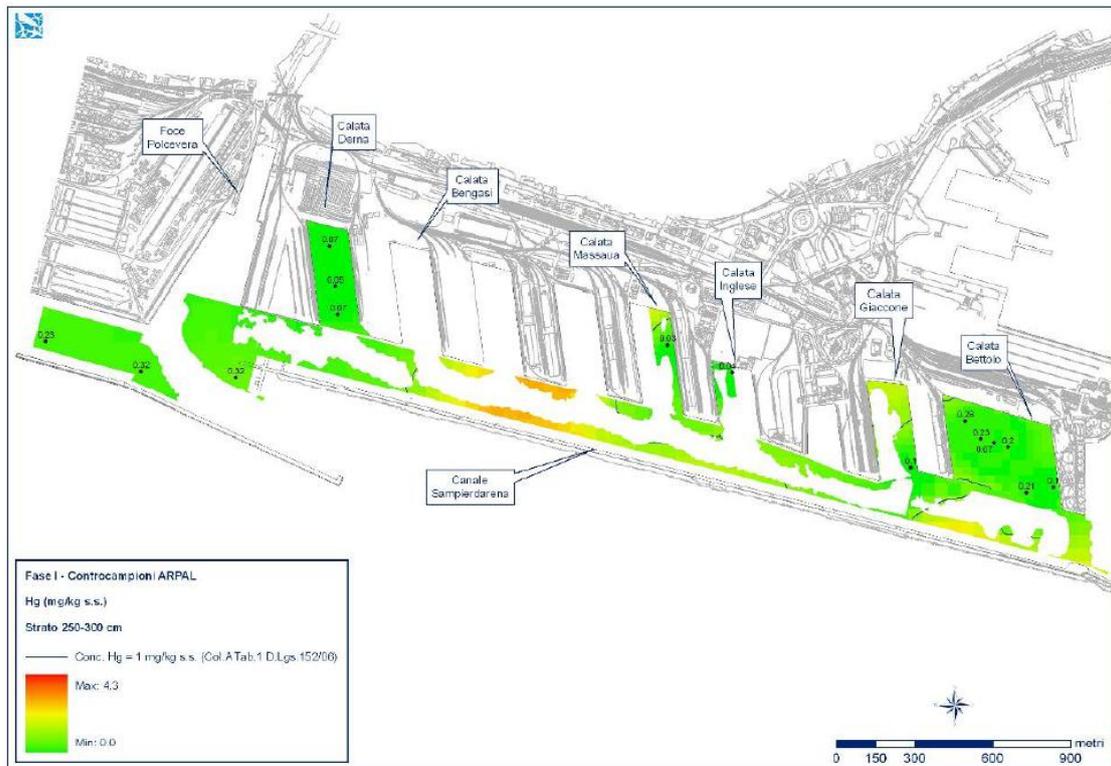
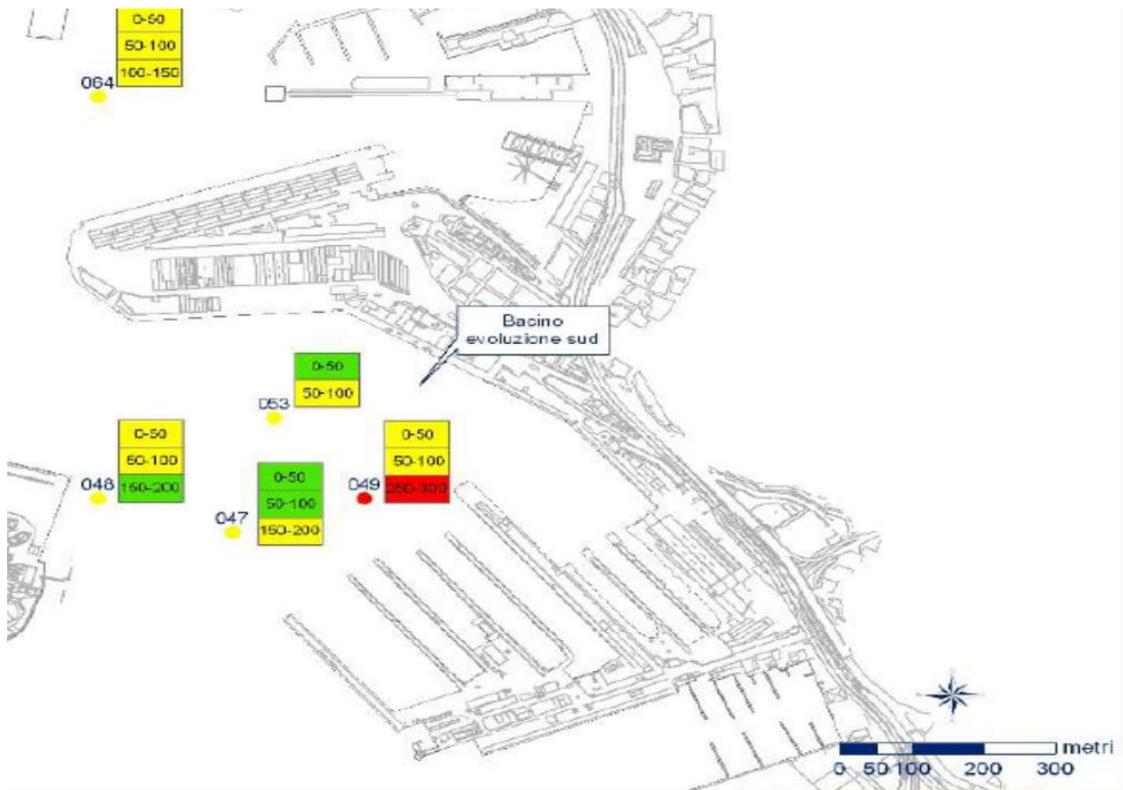


Figure 3.25 - Estimated concentration of Hg in the 250-300 cm layer (ICRAM, 2007)

A total of 34 marine sediment samples were analyzed, belonging to 12 cores taken in Phase II, distributed over several levels, from the surface down to 250-300 cm, for eco-toxicological assessment, carrying out a total of 60 biological tests. The test organisms used were the marine bacterium *Vibrio fischeri* and the sea urchin *Paracentrotus lividus*. Two different environmental matrices were considered: elutriate and

solid phase. The elutriate provides information on the water-soluble fraction of contaminants that is extracted into water by mechanical agitation and represents the most indicative matrix in the case of seabed disturbance. The solid phase provides information about the fraction of contaminants that, due to their chemical nature, non-polarity, solubility, adsorption and degree of complexation with organic matter, remain bound to sediment particles.

The toxicity levels attributed to each sample analyzed are summarized in **Figure 3.26**. On this basis, considering the different specific sensitivity of the organisms used and the different information on the distribution and behavior of the bioavailability of pollutants provided by the matrices analyzed, the following are considered non-toxic samples for which no adverse effects were observed in any of the species used; samples for which one of the two species showed toxic effects are considered to be of low ecological risk; samples for which both species and therefore both matrices showed acute toxic effects are considered to be of high risk.



**Figure 3.26 -** Location of sampling stations for ecotoxicological testing and overall assessment of acute toxicity (ICRAM, 2007)

In 2021, the ISPRA, in collaboration with the Ligurian Regional Agency for Environmental Protection (ARPAL), collected sediments for chemical, physical and ecotoxicological analysis in the framework of the GEREMIA project (Italy-France Interreg Maritime 2021-2020 program; <https://interreg-maritime.eu/web/geremia>). The investigations were conducted at three stations located in different areas representative of the various environmental conditions of the Port of Genoa (eastern entrance, inner port, mouth of the Polcevera Stream). The table (**Table 3.1**) shows the concentrations of trace elements measured in the sediments (GEREMIA, 2021). To obtain a reference for the quality of the sediments analyzed, the analytical results were compared with the Italian national reference chemical levels (L1 and L2) (Table 2.5 – National reference chemical levels in the Technical Annex to D.M. 173/2016). The concentrations of Cd, Cr, Ni, Pb and Zn were always higher than the L1 value at all stations and in all campaigns and, in some cases, even higher than the L2 value. The highest concentrations were measured at the station located in the innermost part of the port and at the station located at the mouth of the Polcevera Stream.

**Table 3.1-** Concentrations of trace elements measured in sediments sampled in the Port of Genoa (mg kg<sup>-1</sup> dry weight). Concentrations above the L1 limit are shown in yellow, while those above the L2 limit are shown in red (table in Italiana and Franch)

Campagna Campagne	Stazione Station	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
I 13/12/2018	Interno porto <i>Intérieur du port</i>	8.78	0.74	64.60	32.93	0.18	43.90	52.95	135.11
	Ingresso di levante <i>Entrée orientale</i>	5.61	0.34	80.11	51.59	0.46	46.32	63.25	162.42
	Foce del Polcevera <i>Embouchure du Polcevera</i>	10.42	0.47	149.19	84.58	0.23	127.04	63.05	226.55
II 16/05/2019	Interno porto <i>Intérieur du port</i>	8.03	0.44	59.14	46.12	0.17	44.82	74.31	143.47
	Ingresso di levante <i>Entrée orientale</i>	13.96	0.41	77.79	78.21	1.36	46.00	92.11	208.00
	Foce del Polcevera <i>Embouchure du Polcevera</i>	5.45	0.37	133.14	88.57	0.23	131.11	59.67	243.72

As part of the project to construct the new breakwater of the Port of Genoa, in 2023 the PerGenova Breakwater Consortium carried out the characterisation of the bottom sediments in the port basin that need to be dredged to deepen the seabed and fill the caissons that make up the new breakwater (PerGenova Breakwater, 2024). The areas affected by the intervention are the eastern entrance to the port and the Sampierdarena Channel (Figure 3.27).



**Figure 3.27-** Area to be dredged in the Sampierdarena basin and at the eastern entrance to the port (PerGenova Breakwater, 2024)

The characterization of sediments was carried out in accordance with the provisions of the technical annex to D.M. 173/2016. Based on the results of integrated chemical-physical and eco-toxicological characterization, five quality classes (A-E) have been identified, ranging from absent to high. Each class has been assigned a color for graphic representation: class A: green; class B: blue; class C: yellow; class D: red; and class E: violet. The summary maps of the sediment classification are shown below (Figure 3.28-3.34).

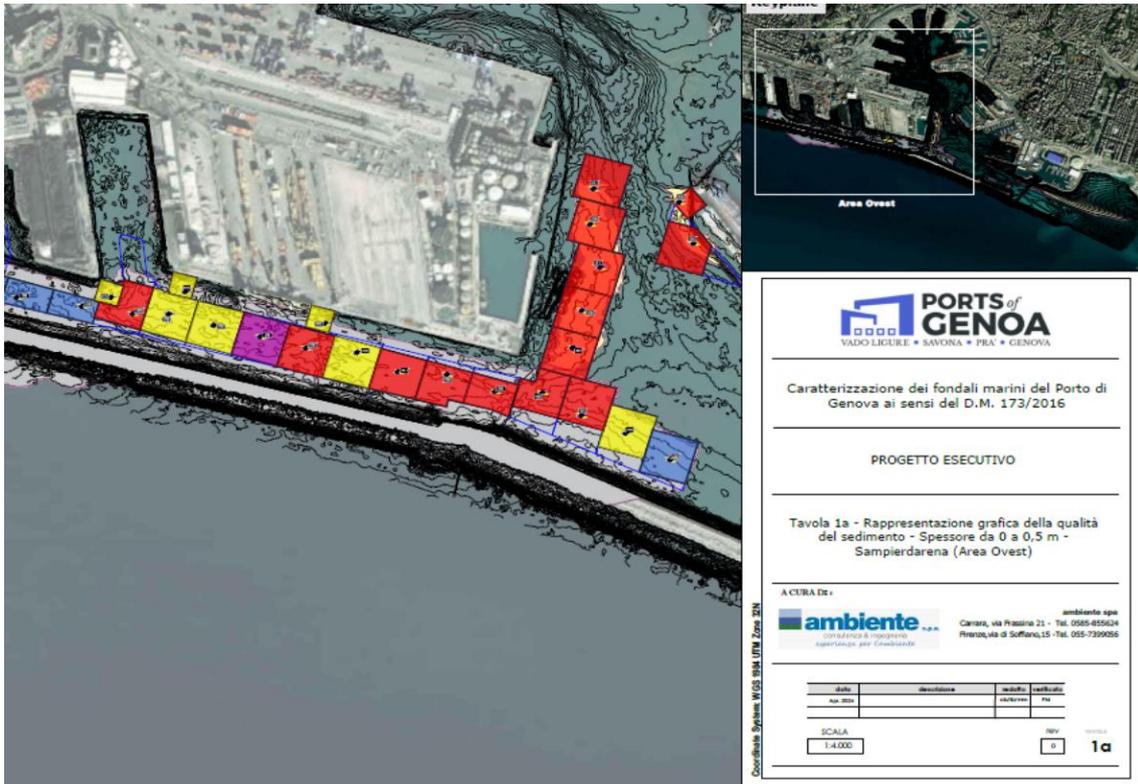


Figure 3.28 - Graphical representation of sediment quality from 0 to 0.5 m depth in the Sampierdarena Channel (PerGenova Breakwater, 2024)

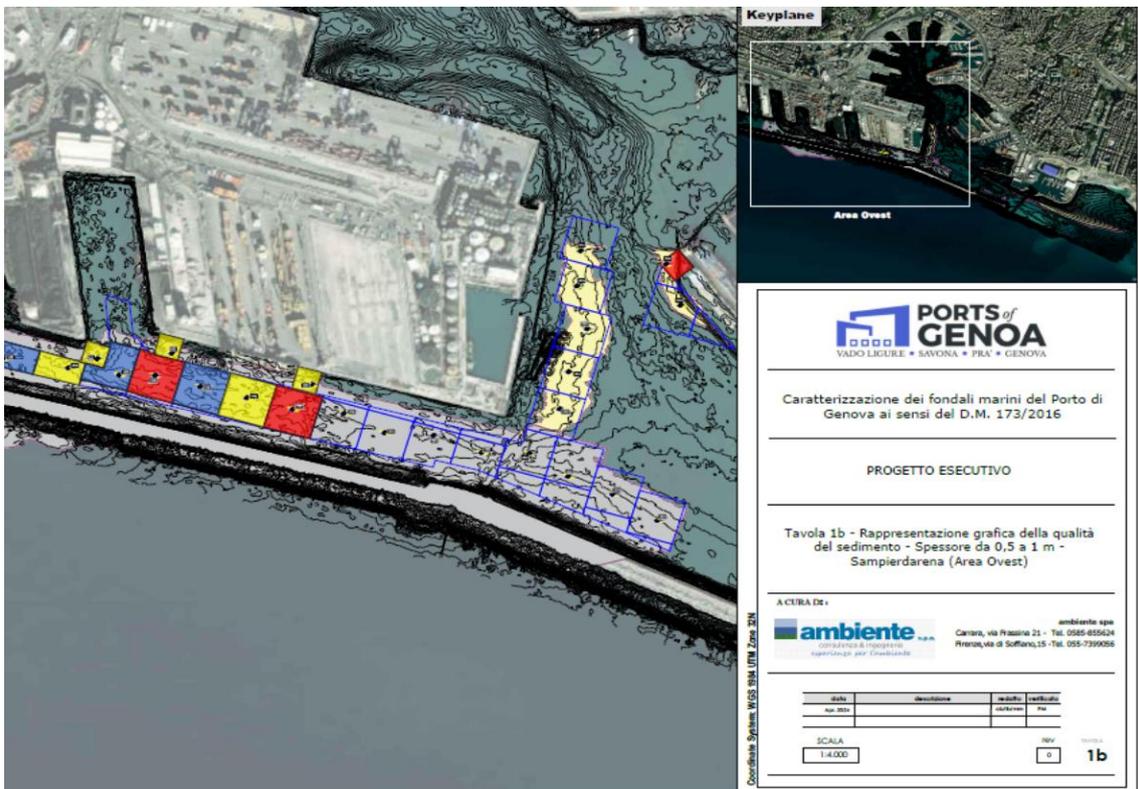


Figure 3.29 - Graphical representation of sediment quality from 0.5 to 1 m depth in the Sampierdarena Channel (PerGenova Breakwater, 2024)

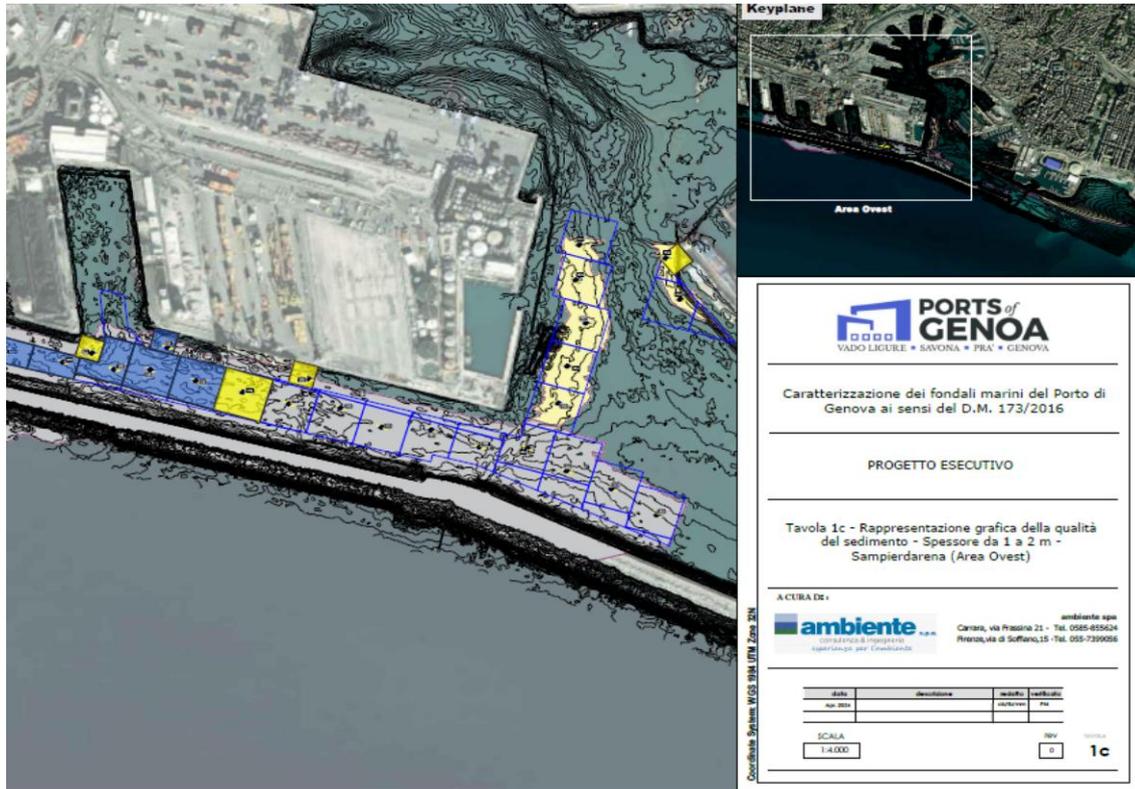


Figure 3.30 - Graphical representation of sediment quality from 1 to 2 m depth in the Sampierdarena Channel (PerGenova Breakwater, 2024)



Figure 3.31 - Graphical representation of sediment quality from 2 to 4 m depth in the Sampierdarena Channel (PerGenova Breakwater, 2024)



Figure 3.32 - Graphical representation of sediment quality from 0 to 0.5 m depth at the eastern entrance (PerGenova Breakwater, 2024)



Figure 3.33 - Graphical representation of sediment quality from 0.5 to 1 m depth at the eastern entrance (PerGenova Breakwater, 2024)



Figure 3.34 - Graphical representation of sediment quality from 1 to 2 m depth at the eastern entrance (PerGenova Breakwater, 2024)

### AUGUSTA BAY SEDIMENT CHARACTERIZATION

The second case study examined, described below, and concerns the characterization plan of the Augusta Harbor. The Priolo SIN, in which the Harbor falls, was established by Ministerial Decree of 10 January 2000 and consists of a delimited marine area that extends from the Augusta Harbor to the Port of Syracuse for a total extension of 8 km and a total surface area of 10161 ha.

In 2008, the Commissioner Delegate for the Reclamation Emergency and Environmental Protection of the Sicily Region at Development Italia Aree Produttive (SIAP), supported by ICRAM, was charged with the environmental characterization aimed at the reclamation of the brackish areas included in the SIN. The characterization plan of the Rada was prepared and developed in two successive phases.

In the first, the characterization of the marine sediments forming part of the so-called "priority areas" and of the biota was carried out, in the second, the sediments falling within the remaining areas called "Phase I completion" were characterized. The subdivision of the Phase had the aim of speeding up the start of the characterization activities in two potentially more critical areas, consisting of a sector between the offshore dam and the external jetty and a more northern one between Ponte Cantera and the mouth of the Marcellino river.

The characterization activity carried out by ICRAM (2008) was based on a dense network of samplings carried out in the study area, characterized by the collection and subsequent analysis of a very high number of samples that involved laboratories of public and private facilities. The large and promiscuous amount of data and results obtained was subjected to verification by ICRAM in order to certify its reliability, based on the verification of the correct application of the sampling protocols by the subjects in charge of the operations. From the comparison of some analyses carried out by ICRAM on a series of representative samples with those carried out by external laboratories, a good correlation emerged for the majority of the samples subjected to verification.

In addition to the analyses on the sediments, in the preliminary phase of the characterization plan, ecotoxicological analyses were also carried out on specimens of marine organisms with different ecological and biological characteristics, representative of the different levels of the trophic network and of significant

importance for food consumption. The aim of these investigations was to detect the concentration levels of pollutants accumulated inside the biological tissues of living organisms present in the Rada. To this end, species of bivalves and benthonectonics were taken into consideration, within which the concentrations of metals, such as mercury, and other bio-accumulative contaminants were detected with greater attention. For the correct execution of the characterization activities, ICRAM provided the bodies carrying out the activities, for each implementation phase, with all the necessary technical documentation. During all the characterization activities, specialized ICRAM personnel were present in the field, for the technical support necessary for the correct application of the specific protocols.

In order not to dwell on the historical description of the investigations, the results of the characterization according to the elaborations proposed by ICRAM are reported below. Please refer to the public and online documentation for further and possible updates.

In any case, it is useful to recall that the interpretation of the results by ICRAM was based on both chemical and eco-toxicological data.

In particular, in order to define the quality of the sediments and the subsequent management, the analytical results were evaluated with respect to specific reference values for each element:

- ICRAM intervention values for the substances for which they were formulated;
- Limit value of column B of Table 1 of Annex 5 to Title V to Part Four of D.L. 152/06 for all the parameters analyzed, for the purposes of the management of contaminated sediments;
- Limit value for the classification of dangerous substances, in line with Annex D of D.L. 152/2006 Part IV - Title I and II, as indicated by art. 1 paragraph 996 of Law no. 296 of 27 December 2006, for the management of contaminated sediments.

Exceeding the limit values listed above concerns three different aspects:

- (1) The presence of the ecological risk related to exceeding the ICRAM intervention values, which are the lowest of the three listed and concern the ecotoxicity of the sediments.
- (2) The presence of the health risk corresponding to exceeding the regulatory limit values, column B Table 1 of Annex 5 to Title V, Part Four of D.L. 152/2006;
- (3) The problem of sediment disposal related finally to exceeding the regulatory limit values of dangerous substances, Annex D, Title I and II, Part Four of D.L. 152\2006.

At the end of the assessments, ICRAM developed a geographical distribution of the concentrations, highlighting the areas of exceedance of each limit value with different colors. The identified areas are:

- **Purple Zone:** This color identifies the areas in which the exceeding of the classification limit values for dangerous substances has been found; in these areas, the highest level of contamination has been found.
- **Red Zone:** The areas in which the concentrations detected are higher than the limit values of Legislative Decree 152/2006 are represented in Red. In these areas, there is the presence of health risk but the concentrations are lower than the classification limit values of dangerous substances.
- **Yellow Zone:** Representing the areas in which the concentrations detected are higher than the ICRAM intervention values, in which therefore the presence of the ecological risk can be attributed, but lower than the limits of D.L. 152/2006.
- **Green Zone:** In these areas, the concentrations found were lower than the ICRAM intervention limit values.

The most significant graphic representations are shown below, in the following pages ([Figures 3.35-3.40](#)).

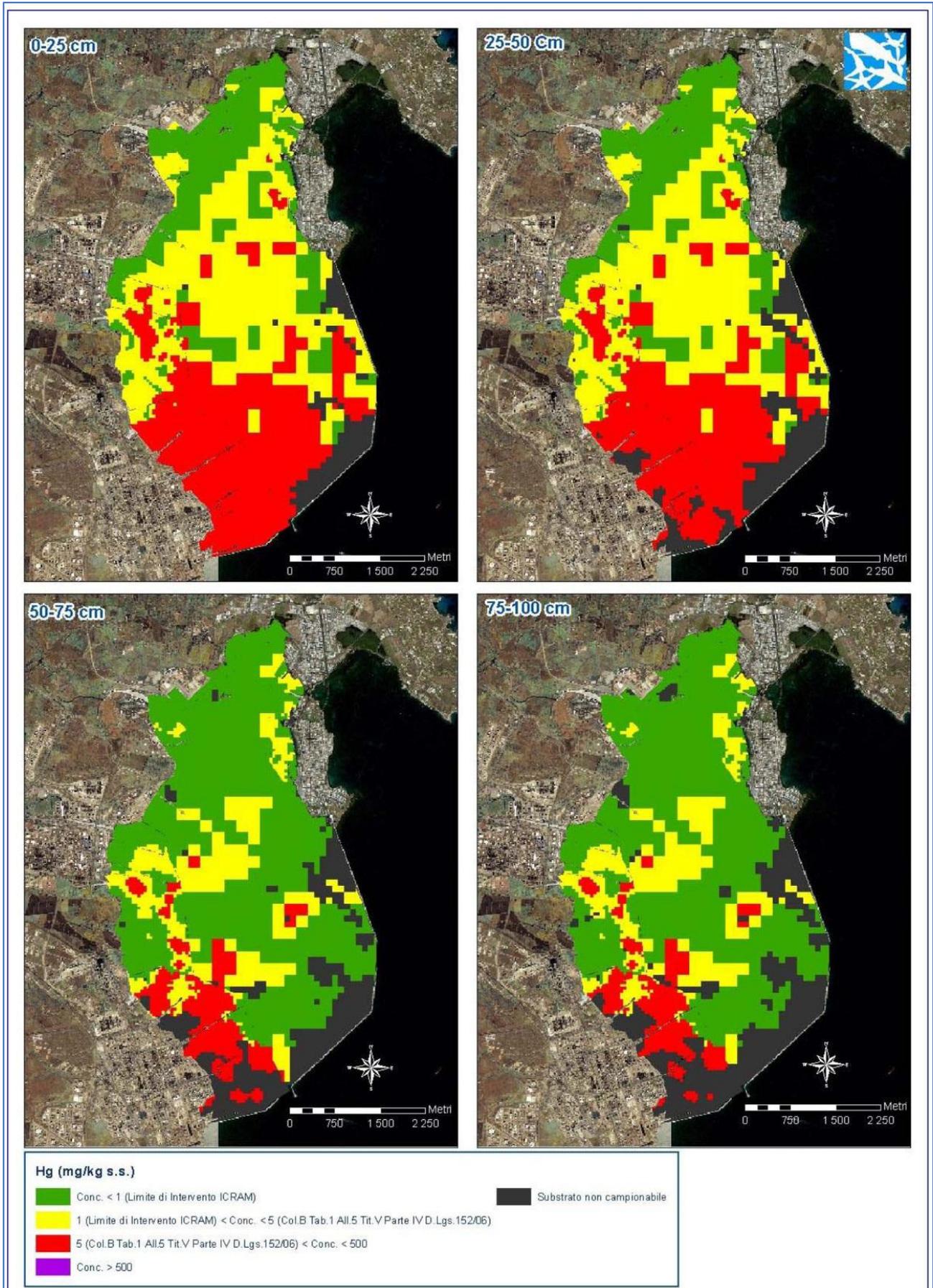


Figure 3.35 - Mercury concentrations in the first 100 cm of sediment thickness. (ICRAM, 2008)

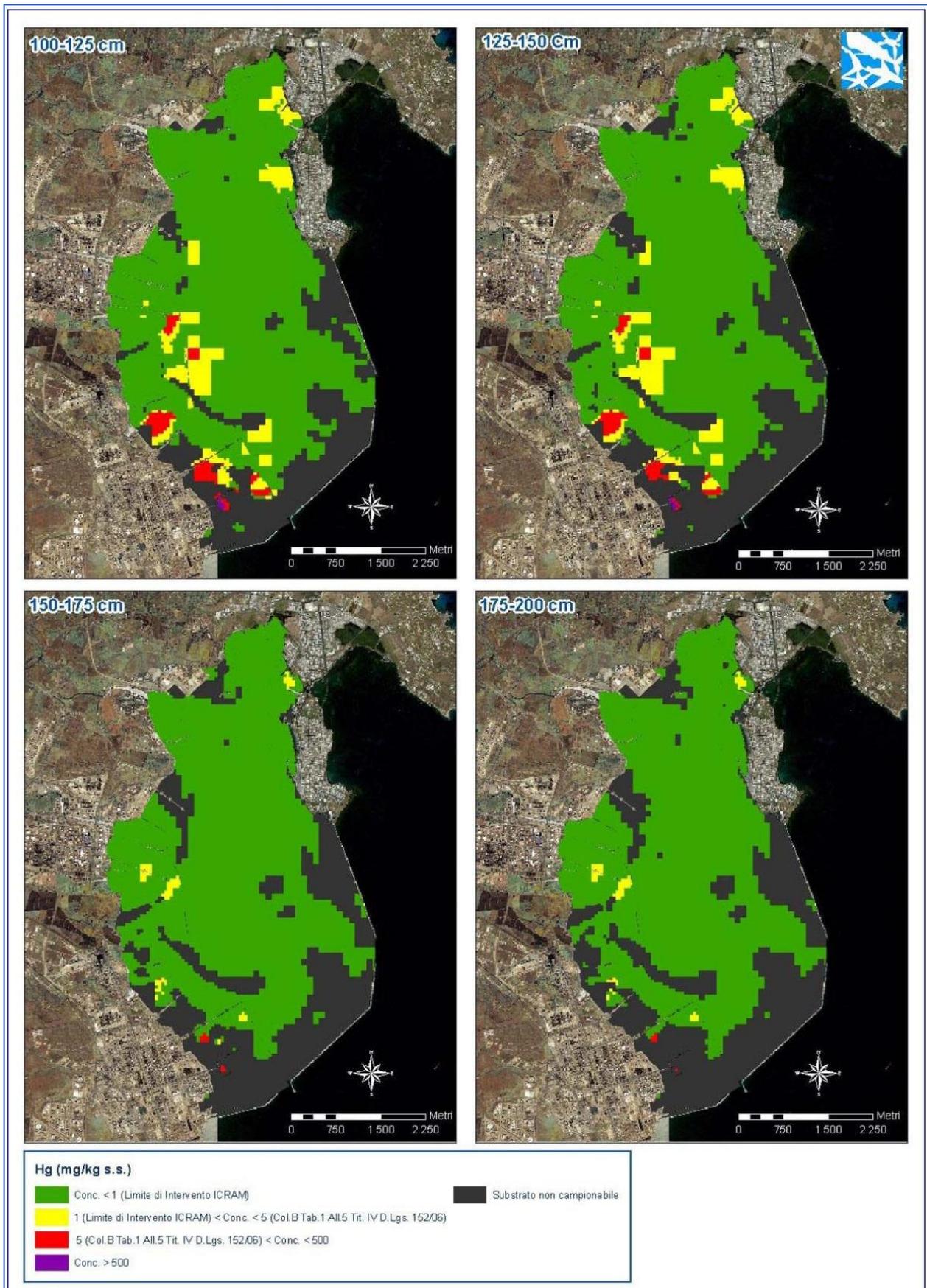


Figure 3.36- Mercury concentrations from 100 to 200 cm of sediment thickness. (ICRAM, 2008)

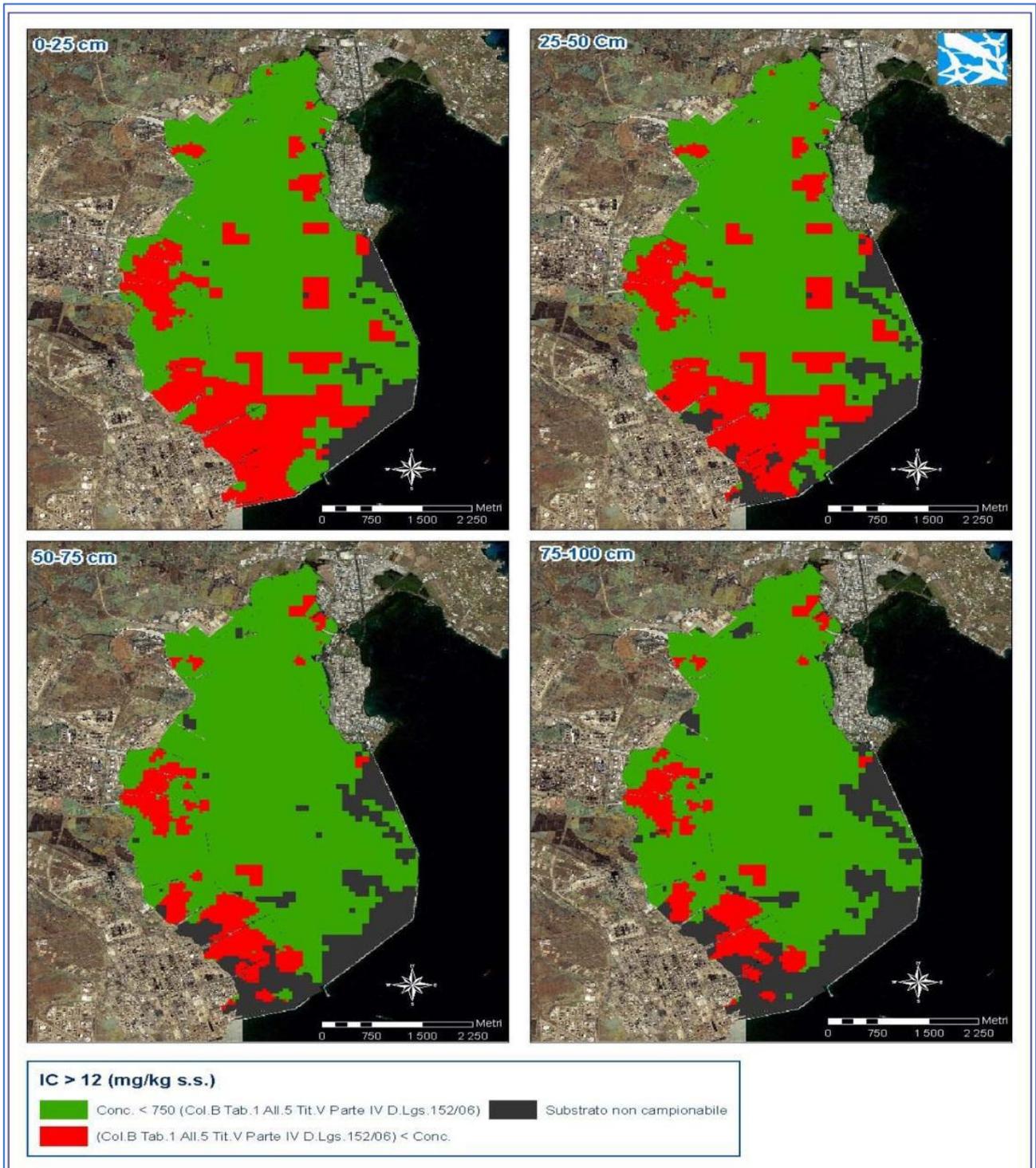


Figure 3.37 - Heavy Hydrocarbons concentration in the first 100 cm of sediment (ICRAM, 2008)

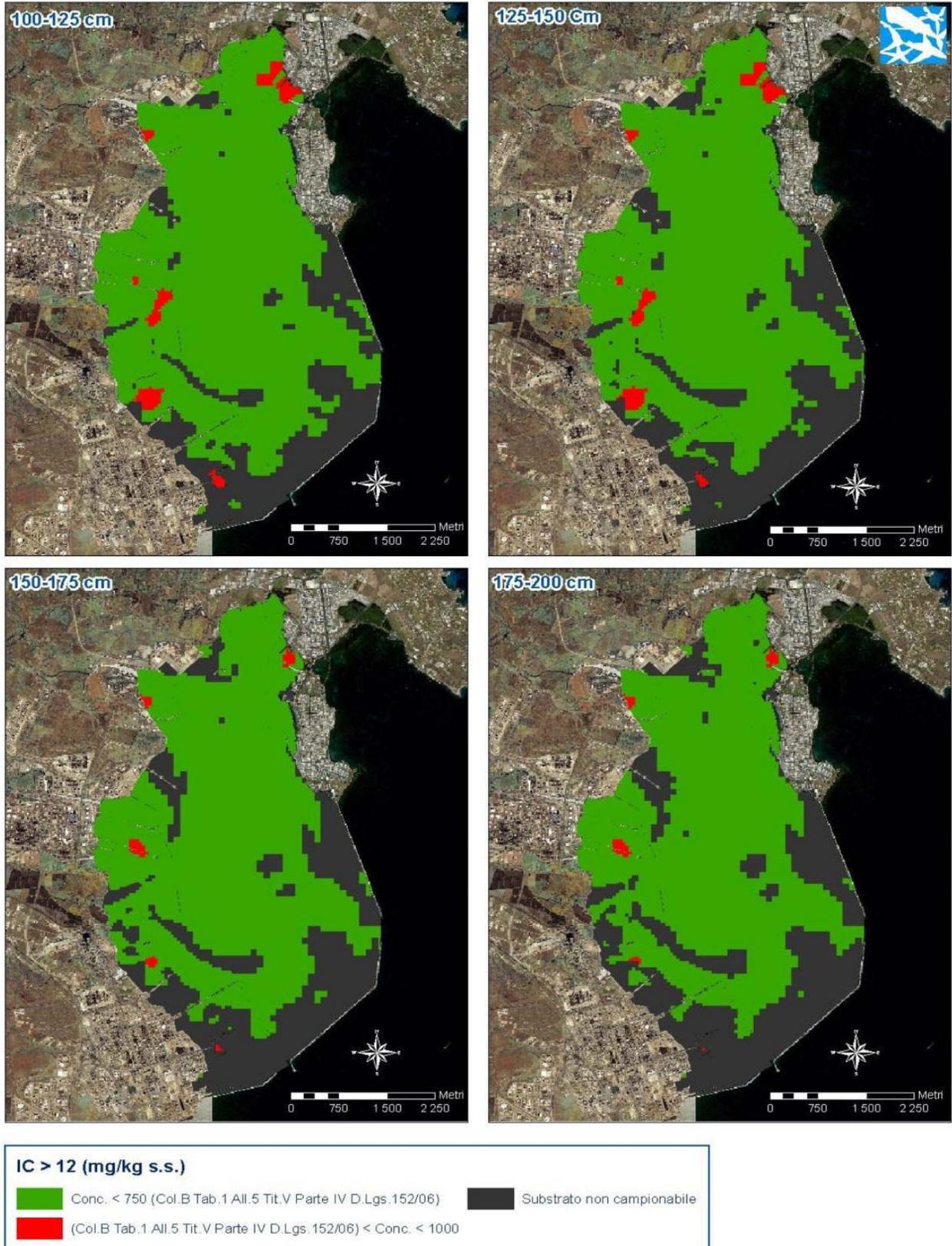


Figure 3.38 - Heavy Hydrocarbons concentration from 100 to 200cm of sediment (ICRAM, 2008)

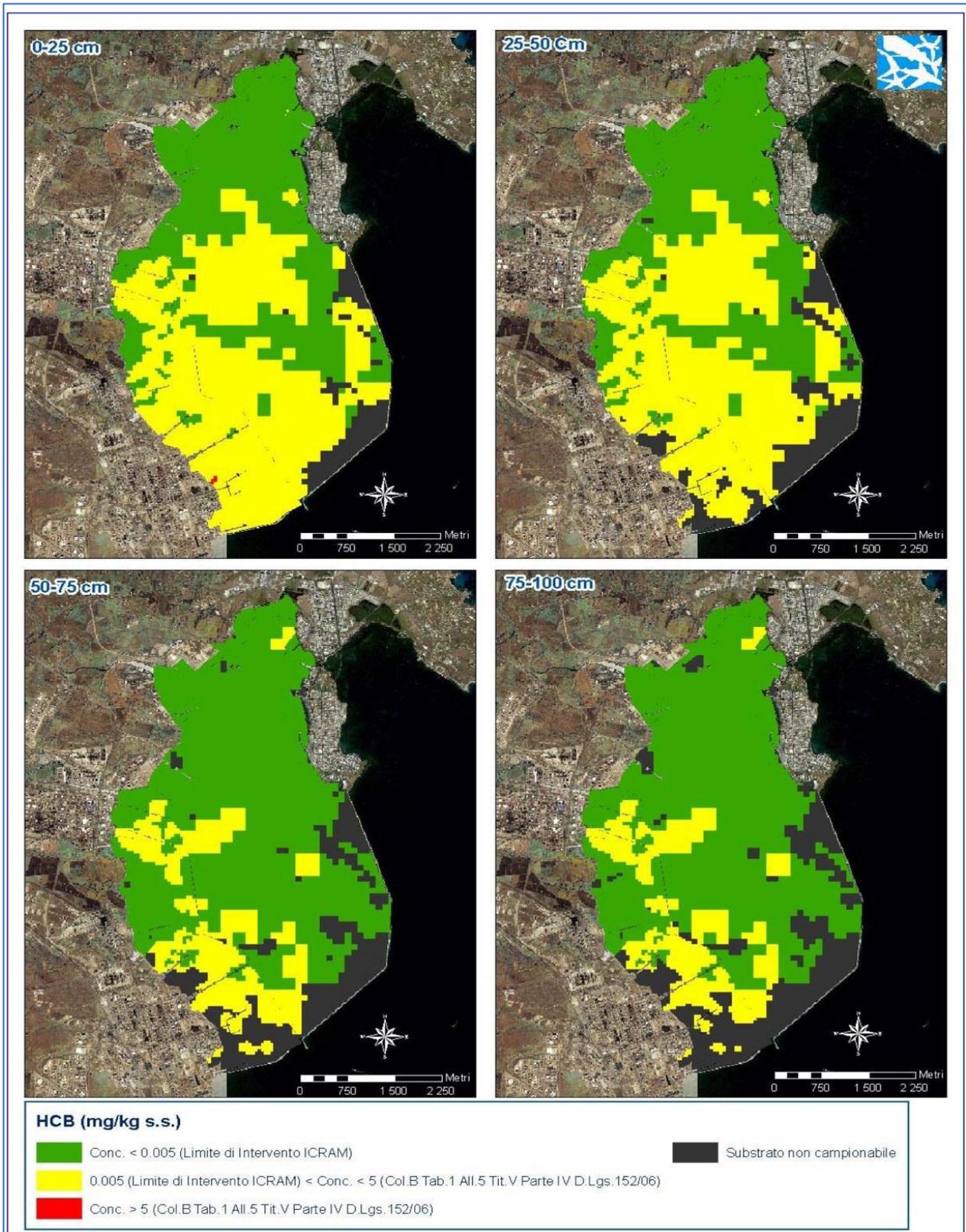


Figure 3.39 - HCB concentration in the first 100 cm of sediment (ICRAM, 2008)

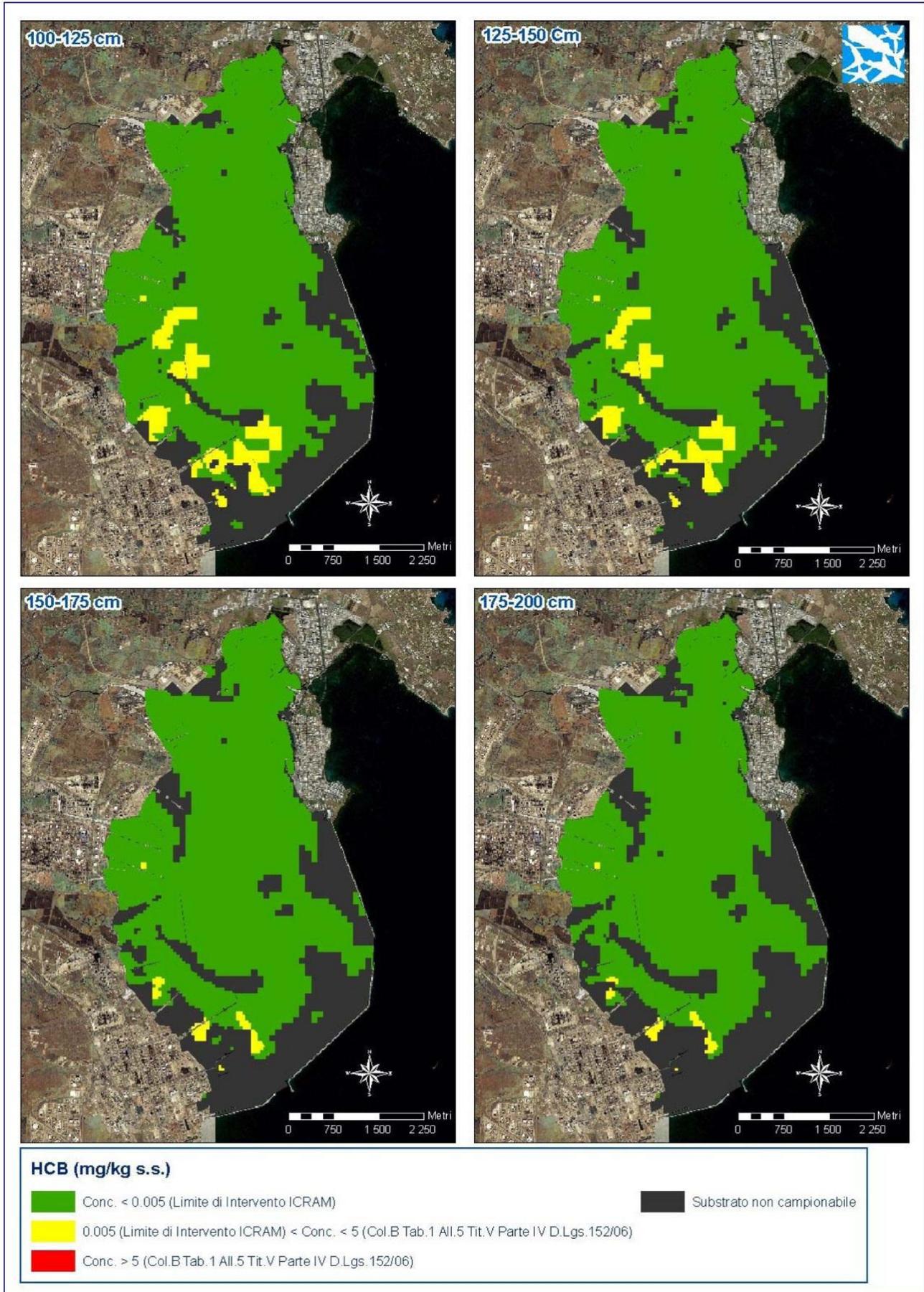


Figure 3.40 - HCB concentrations between 100-200 cm (ICRAM, 2008)

From what emerges from the general characterization carried out by ICRAM, the contaminants of interest, present and relevant, both in terms of chemical and toxicological impact, are HYDROCARBONS and HEAVY METALS (specifically mercury). The technical, impact and remediation studies, which were the object of the study of a part of the project experimentation, were concentrated on these.

## EVALUATION OF DIFFERENT IMPACTS OF DREDGING AND SEDIMENT MOVEMENT IN THE “PROOF OF CONCEPT” AREA

The **Port of Genoa** has employed various dredging methodologies depending on the specific project and the type of material to be removed. These include:

- **Trailing Suction Hopper Dredgers (TSHD):** Used for deepening access channels and reclaiming land by pumping dredged material through pipelines.
- **Backhoe Dredgers:** Utilized for more intrusive dredging, especially in areas with harder materials or near existing structures, sometimes in conjunction with blasting.
- **Cutter Suction Dredgers:** Deployed for various dredging activities within port development projects.
- **Grab Dredgers (GD):** Used in the spreading of sediments accumulated by the mooring maneuvers of ships.

Environmental considerations are significant, often involving the management of potentially contaminated sediments. This has included the creation of lined basins for the containment of dredged material and the implementation of environmental monitoring plans. Monitoring systems, including fixed and mobile stations with turbidity and current measurement instruments, are used to track the impact of dredging activities.

### Important Dredging Projects:

Several significant dredging works have been undertaken in the Port of Genoa to accommodate larger vessels and expand port facilities. Some notable examples include:

- **“Calata Bettolo” Landfill reclamation:** A major project involving a capital dredging of approximately 2.5 million cubic meters of material and land reclamation to create a new container terminal. This aimed to allow access and the mooring for bigger vessels.
- **Ronco Canepa Project:** Included maintenance dredging of about 1 million cubic meters, primarily sand, and land reclamation. This project focused on both port accessibility and river safety.
- **New Breakwater Construction:** This ongoing major project involves significant dredging to create the foundation for the new breakwater, which will allow access for Ultra Large container ships. The dredged material is, in part, being reused in the construction of the breakwater itself. The breakwater's base will reach depths of up to 50 meters (<https://www.portsofgenoa.com/en/new-breakwater-of-genoa/the-project.html>).
- **Upgrading of the Fincantieri Plant:** This includes dredging to adapt the seabed to a depth of -11 meters to accommodate larger ships under construction.
- **Subport Tunnel and Genoa Ring Road (Gronda di Genova):** Two projects carried out by ASPI (Autostrade per l'Italia) to "streamline" city traffic with a tunnel under the port and a bypass of the city area (mainly in a tunnel) of the A12-A7-A10 motorways (the port area is used for landfill reclamation of the "excavated" materials from the work) (<https://www.autostrade.it/en/tunnelsubportualedigenoa>; <https://www.autostrade.it/en/la-nostra-rete/gronda-di-genova>).

These dredging activities are crucial for the ongoing development and competitiveness of the Port of Genoa, enabling it to handle larger ships and increase its capacity.

On the other hand, the dredging and movement operations of the **Augusta harbor** were more specific. Given the state of significant contamination (SIN site) the dredging was limited to strictly necessary operations.

### Dredging Methodologies (General):

Similar to other ports, dredging in the Rada di Augusta likely involves:

- **Suction Dredging:** For removing softer materials like sand and silt. This can include trailing suction hopper dredgers.
- **Mechanical Dredging:** Using backhoe or grab dredgers for more consolidated materials or precise excavation.

The choice of methodology depends on the type of sediment, the depth required, and environmental considerations.

### Important Dredging Projects (Likely Areas):

Dredging in the Rada di Augusta would likely focus on:

- **Maintaining and deepening access channels:** To ensure safe navigation for larger vessels entering the port and industrial areas.
- **Berth deepening:** To accommodate the draft of specific ships at the quays.
- **Potential expansion or infrastructure development:** If new terminals or facilities are planned.

To get specific details on methodologies and projects in the Rada di Augusta, you would need to consult port authority documents, environmental impact assessments related to the port, or specialized maritime and dredging industry publications.

## MATERIALS AND EQUIPMENT USED IN THE LAB EXPERIMENTAL CAMPAIGN

To implement all planned actions and evaluate investigation scenarios, multiple approaches were used. In particular, many of the direct experimentation activities were carried out by means of laboratory-scale plants. In some cases, the kinetic study involved pilot plants with more significant volumes.

From a computational point of view, in order to simulate and predictively investigate the effects of the treatment or management actions, commercial models were applied or specific models were developed.

In order not to create confusion in the reader, it was decided to describe the "materials and methods" directly in the paragraphs in which the different scientific activities are discussed, for each specific experimentation.

The details of the results are reported in the next section

## FOURTH SECTION - RESULTS

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### FURTHER INSIGHT INTO THE CHARACTERIZATION OF THE CONTAMINATION OF THE AUGUSTA HARBOR

Unlike the Port of Genoa, the Rada of Augusta, as mentioned, is significantly polluted. In particular, the great heterogeneity of active sources, or those activated in the past, have compromised the sediments in a historically different way.

It was considered appropriate to deepen the ICRAM investigation, mentioned in the previous paragraph, in order to enrich the contamination information, adding the real "weight" of the exceedances for specific contamination.

Sediment dredging has long been a fundamental operation for maintaining the operating depths that allow the navigability of port areas. Recently, these operations have taken on a new role within a broader context, which includes, when necessary, the remediation of port areas characterized by the presence of contaminated sediments (Legislative Decree 152/06).

This paragraph addresses the issues related to the characterization of port sediments, highlighting the analytical aspects related to the characterization of the sample as is (Tal Qual - t.q.), representative of the environmental state of the in-situ sediments and mainly aimed at evaluating the eco-toxicological and ecological effects, and the characterization of the samples obtained following selection with granulometric fractionation, aimed at subsequent ex-situ treatment operations of the fine fraction for remediation and recovery. Both approaches are fundamental for the evaluation of dredging actions, aimed at remediation and reclamation. On the one hand, however, the characterization of the sediment t.q. can provide more or less direct information on the actual level of ecological risk (ICRAM, 2008), on the other hand, pre-treatment and granulometric fractionation can significantly influence the recovery and reuse operations of sediments after treatment, such as sediment washing or residual disposal (Di Bella et al., 2014, 2015). In this sense, preliminary granulometric fractionation, a technique widely used in the handling of dredged sediments before decontamination treatment, is often applied to reduce the quantity of sediments to be treated, since the prevalent contamination tends to concentrate in the finer fraction (silt and clay).

The further interpretation of the analytical results performed by ICRAM was conducted with the main objective of defining compliance with eco-toxicological standards, such as to define the environmental quality status of the site. In this sense, although some results obtained did not indicate an actual exceeding of the legal limits, the analysis conducted by ICRAM allowed to identify "intervention limits" based on ecological and eco-toxicological aspects, in line with the general direction recently defined by the European Community (Directive 2000/60/EC). In essence, in order to define the quality of the sediments and subsequent management, the analytical results were evaluated with respect to specific reference values for each strategic element, based on the single characterizing aspect:

- for ecological risk: compliance with the ICRAM intervention values for the substances for which they were formulated;
- for health risk: compliance with the limit values in column B of Table 1 of the Annex 5 to Title V to Part Four of Legislative Decree 152/06 for all parameters analyzed, for the purposes of managing contaminated sediments;
- for the final disposal of the residual part: compliance with the limit values for the classification of hazardous substances, in line with Annex D of Legislative Decree 152/2006 Part IV - Title I and II, as indicated by art. 1 paragraph 996 of Law no. 296 of 27 December 2006, for the purposes of managing contaminated sediments.

This approach, although it clarifies and confirms the need for intervention based on eco-toxicological needs, distinguishing the areas according to an increasing chromatic level of "priority" (green, yellow, red, purple), however does not clearly highlight the actual "commitment" of treatment, in terms of "minimum" yields to be achieved for the subsequent treatment. For example, a hydrocarbon concentration of 800 or 3000 mg<sub>TPH</sub>/Kg<sub>SS</sub>, although still falling within the "red zone" (where the concentrations detected were higher than the limit values of Legislative Decree 152/2006, but lower than those for hazardous substances), corresponds to two different treatment needs, such as to guarantee yields of 40-50%, in the first case, higher than 75% in the case of sediments containing approximately 3000 mg<sub>HC</sub>/Kg<sub>SS</sub>.

In order to quantify the degree of exceedance and, therefore, the potential yield required by the remediation intervention, the analytical data reported in the tables attached to the ICRAM study were reworked according to a suitable statistical approach. More specifically, the analysis was carried out considering the most significant sampling areas, divided into 4 geographical areas (north, internal, central and south), and the first 50 cm of sediments. **Figure 4.1** shows the elaborations relating to Mercury and Hydrocarbons.

From an examination of it, it is clear that the most serious situation is due to the high concentrations of Mercury. In particular, in all the sub-areas analyzed, Mercury exceeds all the reference limits, including those of the so-called "ICRAM intervention". The central and southern areas show exceedances of 35-40 times the aforementioned limits. In the same areas, the contamination by hydrocarbons highlights the exceeding of only the limits relating to Legislative Decree 152/06, based on the threshold concentrations of contamination; in this case, the northern and internal areas do not show particular conditions of exceedance, apart from some "hot spots".

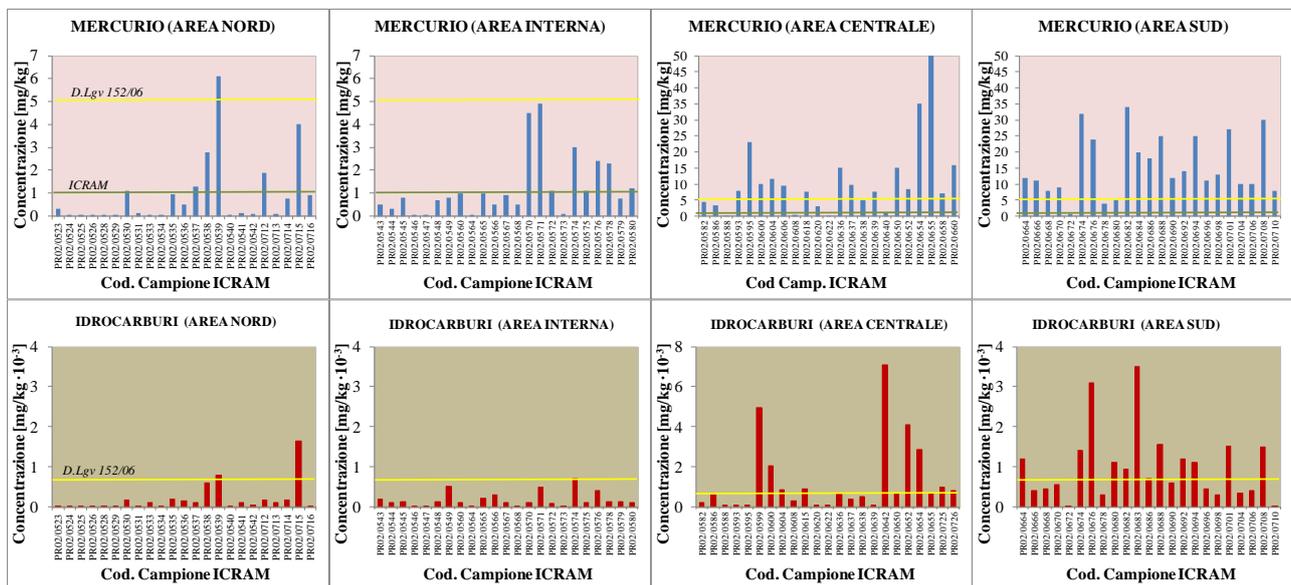


Figure 4.1 - Histograms of concentration of species of interest in the reference areas (references in Italian)

Although the characterization of the sediment as such is the priority starting point for the decision-making approach of intervention, it has been demonstrated that the granulometric separation aimed at the possible recovery of the uncontaminated coarse fraction, if, on the one hand, allows to reduce the weight and volume of the fraction to be subjected to treatment and/or disposal, on the other hand, increases the pollutant removal performance that the possible treatment system must guarantee or the level of environmental protection that the final disposal plant must satisfy with respect to the residual fraction (Di Bella et al., 2014, 2015). In this sense, the chemical characterization of the sample as such is not completely exhaustive for the design of ex-situ remediation interventions of dredged sediments. In particular, if one wishes to reuse dredged sediments, rather than dispose of them, it is necessary to proceed with the characterization, in addition to the sediment as such, also of the granulometric fractions of "interest" in order to verify compliance with the limits

set by the relevant regulations (D.L. 152/2006). In fact, some ex-situ remediation techniques, such as sediment washing, require the pre-treatment of contaminated sediments aimed at separating the granulometric fractions that compose them. This intervention can reduce the quantity of sediments to be subjected to treatment, which can be limited only to the finest fraction (silt and clay), in which most of the pollutants tend to concentrate due to its greater specific surface area; on the other hand, the coarser fraction (sand, gravel) may be uncontaminated and therefore reusable without any treatment.

Figure 4.2 shows the concentration of the two pollutants of interest, mercury and hydrocarbons (in terms of TPH), with reference to the mass of contaminant (in mg) contained in 1 kg of dry sediment, as is or pre-fractionated. The results obtained highlight interesting aspects regarding the applicability of treatments (especially with regard to the real performance required of a hypothetical treatment system) and the general interpretation of pollution (with the possible need to extend the interest to other non-priority contaminants) (Di Bella and Viviani, 2015).

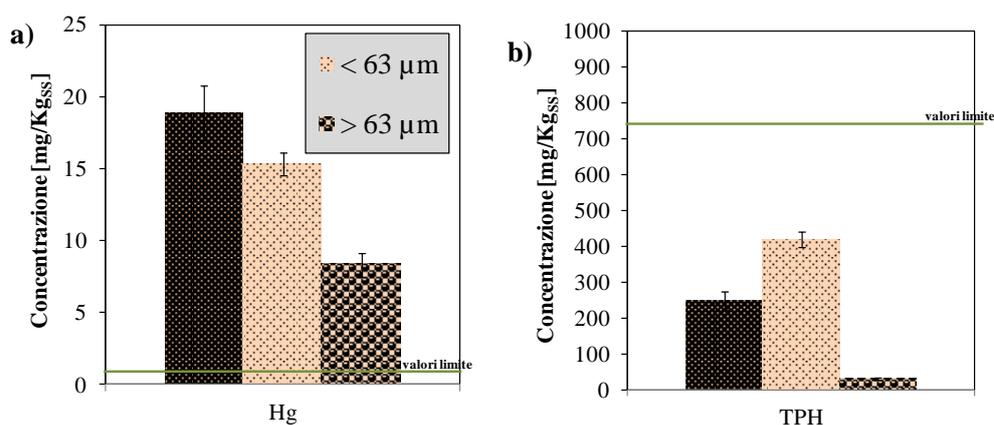


Figure 4.2- Concentrations measured for Hg (a) and TPH (b) in the samples at which, and in the fine and coarse fractions (units of measurement in Italian)

For all samples, contamination is mainly concentrated in the fine fraction; this aspect is particularly marked with regard to pollution of hydrocarbon origin. However, in the samples taken, the concentration of TPH is lower than the regulatory limits of D.L. 152/2006 (750 mg/Kg<sub>SS</sub>), although not negligible and in line with the analyses carried out in 2008.

For mercury, all compliance limits were found to be exceeded: ICRAM "intervention" (1 mg/Kg<sub>SS</sub>); "risk threshold concentration" according to D.L. 152/06 (5 mg/Kg<sub>SS</sub>) and "disposal" according to Annex D of that decree. In addition, in this case, the characterization was conducted for all matrices (as is, coarse and fine) and on all samples. Furthermore, the specific speciation shows that Mercury is not totally concentrated in the fine fraction, which however remains the most contaminated: this circumstance is attributable to the various forms in which Mercury can be found (soluble, weakly or strongly bound).

The preliminary characterization analysis of the sediments has highlighted the different role that pollutants can have, depending on the granulometric characteristics of the fractions in which they can be found. This is of particular interest in the preliminary phases of evaluating the possible treatment, recovery or disposal interventions to which the sediments themselves can be subjected; in fact, even in cases where it is possible to separate an uncontaminated coarse fraction to be sent for recovery, there remains the need to treat or dispose of the fine fraction, whose state of contamination will be higher the greater the coarse fraction previously separated. In this sense, the characterization of the sediments as such is certainly exhaustive for defining the need for intervention, but it is not exhaustive for the purpose of identifying the possible treatment interventions that can be adopted to constitute a by-product sent for recovery or, alternatively, to send the sediments for disposal as waste.

## RESULTS OF IN-DEPTH EXPERIMENTAL INVESTIGATIONS ON FEASIBLE TREATMENTS

Below are the experiments that have produced concrete and externalizable results thanks to the project funding. As previously discussed, it was decided to present each experiment individually, including for each specific activity, materials, methods, and results.

In the following a list of the main publications externalized on RETURN

### BIOSLURRY

1. Assessment on the effect of erythromycin on the microbiome of a bioslurry pilot plant for contaminated sediment bioprocessing. JOURNAL: Bioresource Technology Reports Volume 23 September 2023 Article number 101532 ISSN: 2589014X

### THERMAL DESORPTION

2. Application of Low Temperature Thermal Desorption of marine sediments: operational and management assessment. PROCEEDING: SIDISA 2024 XII International Symposium on Environmental Engineering Palermo, Italy, October 1 – 4, 2024
3. Thermal desorption of marine contaminated sediments: analysis of performance at Low-Temperature process condition. JOURNAL: Journal of Environment Management JEMA-D-25-26400 (SUBMITTED)
4. Desorbimento termico a basse temperature di sedimenti marini contaminati: valutazioni operative e gestionali. Journal: Ingegneria dell'Ambiente Vol. 12 n. 2/2025

### SEDIMENT WASHING

5. Surfactant enhanced remediation of marine sediments using anionic, non-ionic and mixed surfactants: role of operational conditions. PROCEEDING: SIDISA 2024 XII International Symposium on Environmental Engineering Palermo, Italy, October 1 – 4, 2024
6. Bonifica dei sedimenti marini contaminati mediante l'uso di tensioattivi singoli e misti: efficienze di rimozione e fitotossicità residua. PROCEEDING: SiCon 2025 Workshop su: Siti Contaminati. Esperienze negli interventi di risanamento
7. Ossidazione chimica di suoli e sedimenti contaminati con Ferrato(VI) di potassio potenziato da tensioattivo: valutazione delle performance e confronto con Permanganato di potassio. PROCEEDING: SiCon 2025 Workshop su: Siti Contaminati. Esperienze negli interventi di risanamento
8. Role of mixed surfactants for hydrocarbons removal from real marine sediments: Removal efficiency and residual phytotoxicity after sediment washing treatment. Journal: Journal of Environmental Chemical Engineering 13 (2025) 119873. <https://doi.org/10.1016/j.jece.2025.119873>.

### GENERAL PRESENTATION

9. Pilot plant for contaminated sediment bioprocessing The Italian National Recovery and Resilience Plan (PNRR) RETURN Project: proposal of new monitoring and bioremediation protocols in the pilot site of the Port of Genoa. PROCEEDINGS - Rhodes 2024

## BIOLOGICAL TREATMENT: BIOSLURRY FOR REAL SEDIMENT

### ➤ INTRODUCTION

Referring to the purely laboratory aspects, among the first research conducted within the project, the analysis of the bioremediation of real sediments was particularly interesting. The study followed the results of previous experiments conducted before the project was funded: in this context, the new studies produced concerned advanced aspects of homework, in continuity with the experiences historically carried out by the research groups of the universities of Enna "kore" and Palermo. In particular, the experimentation concerned the applicability of bioslurry treatment to contaminated marine sediments, whose results refer to the studies conducted by **Di Bella et al. (2023) published on BIORESOURCE TECHNOLOGIES REPORTS**

As briefly discussed above, bioslurry is a microbial-based technology that uses a bioreactor to treat sediments. The role of microbial metabolic capabilities is crucial for the removal performance of this

technology and those factors that can affect microbial community. Particularly, antibiotics are among the environmental emerging contaminants. In this work, the effect of erythromycin was evaluated on the removal efficiencies of total petroleum hydrocarbons (TPHs), present in real sediments. Particularly, in the last year, among bioremediation approaches the microbial-based bioslurry technology has been considered for the treatment in close or open bioreactors of sediments or soils to treat contaminated by a wide range of recalcitrant organic pollutants such as fuels, pesticides, creosote, polychlorinated biphenyls (PCBs), TPHs and some halogenated volatile organics.

In a bioslurry system, water-sediment slurry is mixed with appropriate microorganisms under controlled aerobic conditions. Bioslurry systems often operate in batch mode, with a typical retention time lasting 2–12 weeks, and once the treatment period is completed, the solids may be separated from the water and disposed (Avona et al., 2022; Robles-González et al., 2008).

Thus, considering the possible relationships between TPH removal capability and antibiotic resistance of bacterial microbiota members as highlighted by the co-occurrence of antibiotic resistance genes (ARGs) in polyaromatic hydrocarbon degraders (Cunningham et al., 2020; Maurya et al., 2021), the aim of the work was to investigate how the presence of erythromycin can modulate the microbiome by changing the microbiota structure and, thus, the removal efficacy of bioslurry system set up for the treatment of real sediment samples to remove TPHs.

## ➤ MATERIALS AND METHODS

The marine sediment samples used for the experimental campaign were collected from the northern part of Augusta Bay, near petrochemical plants (Falciglia et al., 2020; Lumia et al., 2020a; Lumia et al., 2020b). Regarding the analysis of dredged marine sediments, they revealed a slightly acidic nature (pH 6.60) with a higher content of sand (42.36 %), followed by silt (35.38 %) and clay (22.27 %). The sediment has a high concentration of moisture content (48.6 %), organic matter (4.7 %), density (2.57 g cm<sup>-3</sup>) and conductivity (5 mS cm<sup>-1</sup>). In terms of contaminant content, marine sediments were affected by a severe hydrocarbon contamination with a detected TPH level of 888.57 mg<sub>TPH</sub> kg<sub>DW</sub><sup>-1</sup>, higher than the limit of 750 mg<sub>TPH</sub> kg<sub>DW</sub><sup>-1</sup> imposed by the Italian legislation.

The detailed characterization of sediments was shown in the paper: particularly, in order to complete the information, in Table 4.1 also the activated sludge properties, used for initial inoculum, were reported.

Table 4.1 Properties of sludge and marine sediment of Augusta Bay.

Activated Sludge	
Total Carbon (mg L <sup>-1</sup> )	9.84
Total Organic Carbon (mg L <sup>-1</sup> )	1.18
EC (mS cm <sup>-1</sup> )	1050
Total solids (g L <sup>-1</sup> )	3.1
Volatile solids (g L <sup>-1</sup> )	0.35
Marine sediment	
Physical properties	Value
Density (g cm <sup>-3</sup> )	2.57
pH	6.6
EC (mS cm <sup>-1</sup> )	5
Moisture content (%)	48.6
Organic matter (%)	4.7
Particle size distribution	Fraction (%)
Sand	42.36
Silt	35.38
Clay	22.27
TPH content	Concentration (mg <sub>TPH</sub> kg <sub>DW</sub> <sup>-1</sup> )
Σ TPH fractions (C <sub>12</sub> -C <sub>40</sub> )	888.57

Concerning the experimental campaign, a series of preliminary microcosm tests were carried-out in order to define the general influence of erythromycin dosage. Then, the subsequent experiments, performed in bioslurry pilot plants, were based on the microcosm results.

In particular, the pilot plant (Figure 4.3) experimental installation was characterized by the preparation of two bioslurry reactors called "R1" and "R2", respectively, that were started up with an initial bioaugmentation of activated sludge collected by a full-scale WWTP (Enna, Sicily). Specifically, the experimental campaign was divided into 3 phases, for a total period of 75 days: PHASE 1, lasting 30 days, during which R1 and R2 had the same characteristics and operating conditions; PHASE 2, spanning from 31<sup>st</sup> to 60<sup>th</sup> day, during which the erythromycin ( $0.5 \mu\text{g mL}^{-1}$ ) was added into R2 reactor; PHASE 3, spanning from 61<sup>st</sup> to 75<sup>th</sup> day, characterized by the replacement of liquid phase of both reactors with saline water, in order to deepen the study on microbial behavior.

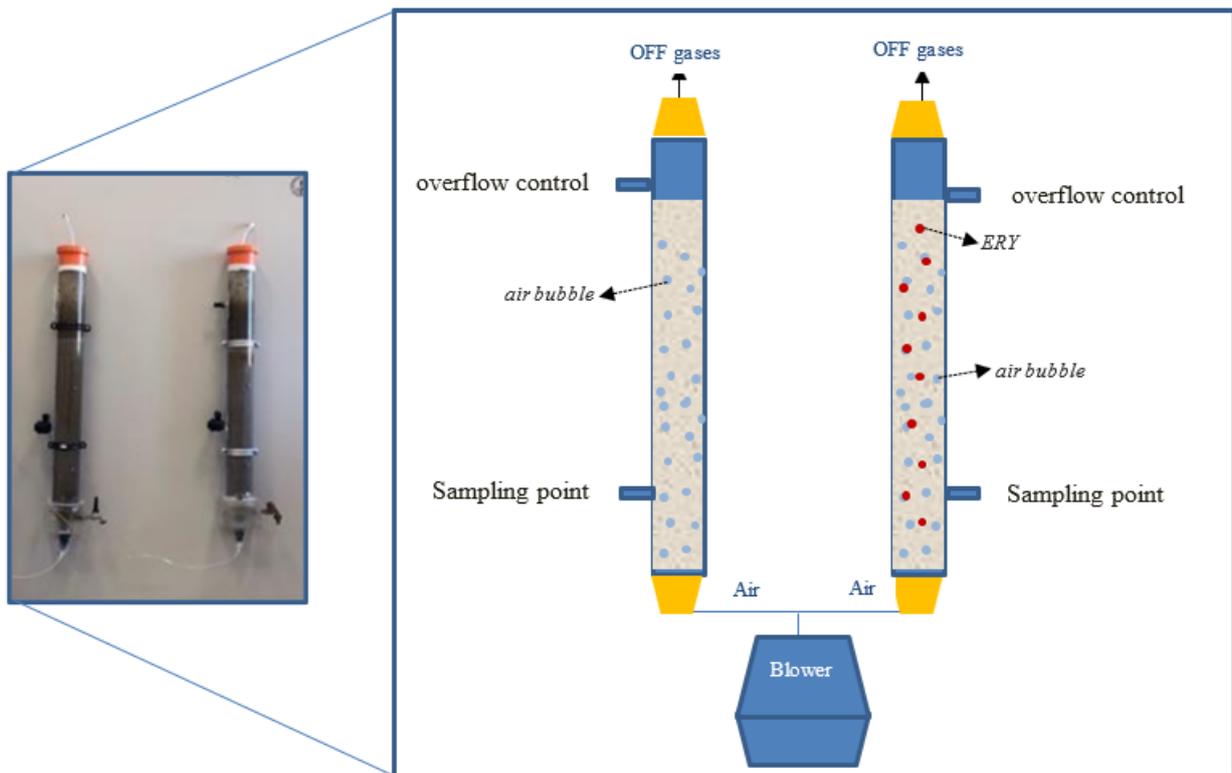


Figure 4.3 - BIOSLURRY Pilot plant scheme.

At the beginning, batch tests were conducted in order to identify the optimal erythromycin concentration and to evaluate its effect on the biodegradation activity of pollutants by a halotolerant microbial inoculum. The latter was previously acclimatized through a cultivation with a semi-continuous supply of civil wastewater with increasing salinity. These tests have been divided into two activities. The first activity was conducted by using five different concentrations of erythromycin (e.g., 0.05, 0.1, 0.5, 1, 5  $\mu\text{g mL}^{-1}$ , respectively) in flasks (i.e., "small volume", 0.1 L) containing also biomass (sludge) and water in a ratio of 1:10 (v/v). The suspension was kept stirring by an orbital shaker at a speed of 150 RPM. In order to evaluate the microbial biodegradation activity under the effect of erythromycin, it was decided to monitor the variation of the concentrations of Total Carbon (TC) and Total Organic Carbon (TOC) after 30 min, 1 h, 24 h and 96 h. The results obtained were compared with the values of the control test in which no antibiotic dosage was performed.

The second activity was planned on the basis of first activity results. Specifically, with reference to the "optimal dosage" obtained from the first battery of tests, the study was deepened by evaluating the effect of antibiotic presence on TPH biodegradation. For this purpose, the test was carried out in a volume of 1 L (i.e. "large volume") consisting of water and activated sludge, in which 100 g of sediment were added in a ratio

equal to 1:10 (w/v) and the antibiotic was dosed to optimal concentration value ( $0.5 \mu\text{g mL}^{-1}$ , please, see Results and discussion section). In addition, in this case, the system was shaken and the TOC concentrations and the residual concentrations of TPHs present in the liquid phase and sediment were analyzed (after the contact time of 1 h, 24 h and 96 h of incubation). The subsequent investigation campaign was performed setting a pilot plant system characterized by two bioslurry phase reactors each having 4 L working volume. They were fabricated using plexiglass with height/diameter (H/D) ratio equal to 10. Air diffusers connected to the sparger network using silicon tubing were provided at the bottom of the reactor (2 mm above the reactor bottom) to facilitate uniform distribution of air through the system. Air flow rate was set at  $3 \text{ L min}^{-1}$ , chosen based on mixing tests conducted with varying air flow (the data are not reported in this work). In each reactor 400 g of contaminated sediment and 4 L of water in a ratio, 1:10 (w/v) were mixed. Furthermore, initially nutrients and activated sludge were added in the bioslurry. Nutrients ( $\text{CH}_3\text{COONa}$  [ $35 \text{ g L}^{-1}$ ],  $\text{NH}_4\text{Cl}$  [ $7 \text{ g L}^{-1}$ ],  $\text{K}_2\text{HPO}_4$  [ $2 \text{ g L}^{-1}$ ],  $\text{CaCl}_2$  [ $1.5 \text{ g L}^{-1}$ ],  $\text{MgSO}_4$  [ $1.2 \text{ g L}^{-1}$ ]) were added at the beginning of the study to achieve a carbon/nitrogen/phosphorus (C:N:P) molar ratio of 100:10:1 based on the hydrocarbon loading as a measure of C (Avona et al., 2022a; Avona et al., 2022b). Activated sludge (100 mL) was collected from the wastewater treatment plant of Enna in order to favor the bioaugmentation of sediment.

As discussed above, the experimental campaign lasted 75 days in total, subdivided in three different periods referred as PHASE 1–3, respectively. In PHASE 1 of the experimentation, from the day 1<sup>st</sup> to the 30<sup>th</sup>, both reactors worked with the same operating conditions. Subsequently, in PHASE 2 (from the 31<sup>st</sup> day to the 60<sup>th</sup> day), in the R2 reactor the erythromycin was added to the concentration of  $0.5 \mu\text{g L}^{-1}$ , chosen based on microcosm tests. Finally, after the 60<sup>th</sup> day, the liquid phase of both reactors was replaced with tap water (in which NaCl was added, in order to obtain the same conductivity present in the reactors). This last PHASE was performed in order to investigate the probable rebound effect (Lumia et al., 2020b). For both reactors, sediment and bioslurry (i.e., solid phase) samples were taken every two weeks in triplicate for chemical analyses. In addition, at 45<sup>th</sup>, 60<sup>th</sup> e 75<sup>th</sup> day both the aqueous and the solid phases were sampled to perform TPH concentration and microbiological analyses.

During the bioprocesses, several operational variables can be monitored and controlled: pH, temperature and, in aerobic bioslurry, Dissolved Oxygen (DO). Particularly, pH is one of the important parameters, which influences the activity and type of microbiota and substrate mobility. The temperature was in a range between  $25 \text{ }^\circ\text{C}$  and  $30 \text{ }^\circ\text{C}$  that is reported as optimal value for treatment in both reactors during the experimentation. Finally, for off-gas monitoring (mainly  $\text{CO}_2$ ), an on-line detector was used: online Photo-Ionization Detector – PID. The exhausted air of the reactor was collected towards the instrument, which measured the variation of  $\text{CO}_2$  (and oxygen, for compensation). The system was installed periodically once the stationary phase of the phase was reached.

## ➤ MAIN RESULTS

In small volume tests, the variation of TC and TOC concentrations were evaluated with reference to different incubation times (i.e. 0.5, 1, 24, and 96 h) and different erythromycin concentrations (i.e. 0.05, 0.1, 0.5, and  $5 \mu\text{g mL}^{-1}$ ). In general, at the concentrations of 0.1, 0.5 and  $1 \mu\text{g mL}^{-1}$  the TC and TOC values are quite stable after 0.5 and 1 h of activity (Figure 4.4), and partially after 24 h. On the contrary, the variations of the antibiotic response at 96 h prove to be heterogeneous at all used antibiotic concentrations. Interestingly, the results of TOC concentrations in the respect of erythromycin concentration and exposure time in small volume microcosm tests suggested that the antibiotic addition affected microbial activity and growth. In fact, different studies suggest a correlation between TOC and microbial growth even if it is complex to define a general behavior. Indeed, the presence of organic compound promotes the growth of heterotrophic microorganisms (Williams et al., 2015; Lehtola et al., 2002). In the microcosm analysis, different erythromycin concentrations were used highlighting an optimal antibiotic dosage below which the effect on TOC concentration is not appreciable and above which the effect can be negative. In particular, at 0.1, 0.5 and  $1 \mu\text{g mL}^{-1}$  of erythromycin, TOC concentrations increased compared to the initial value of  $1.18 \text{ mg L}^{-1}$  at 24 h (data not shown) while at 96 h TOC concentration was observed for 1 and  $5 \mu\text{g mL}^{-1}$  erythromycin concentrations. This implies that TOC is positively correlated with erythromycin concentrations that are probably too high and harmful for bacterial

growth. Indeed, erythromycin usually has a minimal inhibitory concentration against bacteria ranging from  $\leq 0.25$  to  $1 \mu\text{g mL}^{-1}$  (Ge et al., 2017; Fenton and Buckley, 2015): on the basis of the above-mentioned evidence, for the subsequent analyses, an antibiotic concentration of  $0.5 \mu\text{g mL}^{-1}$  was considered with a maximum incubation time of 24 h (Lumia et al., 2020b).

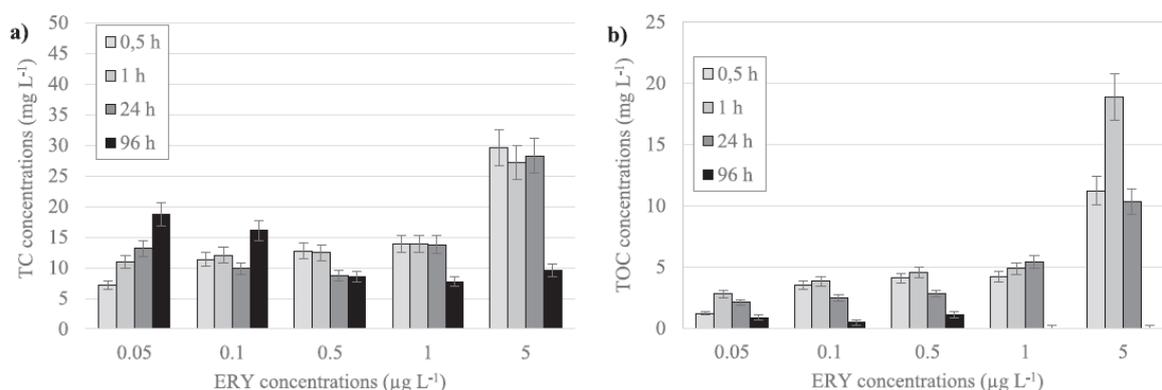


Figure 4.4- Influence of erythromycin concentrations on TC (a) and TOC (b) variations. ERY: erythromycin (By Di Bella et al., 2023)

Subsequently, microcosm testing continued by analyzing a further batch test, mixing water and sediments in large volume (1 L) assays adding the antibiotic based on the best dosage previously detected (Figure 4.5). This analysis showed that TOC concentration increased rapidly from  $1.5$  to  $2.44 \mu\text{g mL}^{-1}$  after the first 24 h, remaining stable at around  $2.2$ – $2.3 \mu\text{g mL}^{-1}$  in the following three days. This observation paralleled the 12–15 % removal of TPHs from the microcosm sediments in just 4 days, going from  $888 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DW}}^{-1}$  to  $777 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DW}}^{-1}$ . Based on these encouraging results, it was decided to dose the antibiotic directly in the pilot plant column and study the potentially stimulating effect of erythromycin during the continuous treatment of sediments with bioslurry. The results obtained in large volume microcosm tests confirm and validate the data obtained in the small volume microcosm assays. In particular, it appears that by injecting  $0.5 \mu\text{g mL}^{-1}$  of erythromycin the microbial cells of the bioslurry system manage to survive and, based on the temporal evolution of the TOC and TPH values, it seems that the erythromycin selective pressure parallels metabolic adaptation to the presence of TPHs in the sediments whose concentration decrease of 15 % in 4 days.

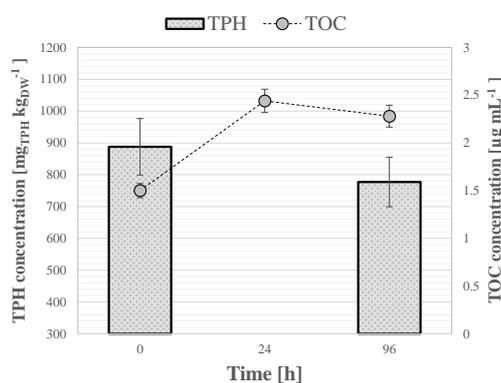


Figure 4.5- Batch test (in large volume) for TPH evaluation (— error bar)

The degradation patterns of TPHs in solid and liquid phases, for the reactors R1 e R2, are shown in Figure 4.6. In PHASE I of pilot plant experimentation, both reactors present the same operating conditions and, in this case, TPH residual concentrations in the solid phase resulted quite similar being  $558.93 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DW}}^{-1}$  for R1 and  $564. \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DW}}^{-1}$  for R2, with a RE of 37 % in R1 and 36 % in R2.

Subsequently, in PHASE 2, in R2 reactor  $0.5 \mu\text{g L}^{-1}$  erythromycin was dosed. In this PHASE, in R1 reactor the removal efficiency slight improved in comparison with PHASE 1 (Fig. 2) reaching at the end of PHASE 2 a value equal to  $333.33 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DW}}^{-1}$  (RE = 62.5 %); in PHASE 2 of R2 the TPH removal rate increases much more in comparison to R1, so that the TPH residual concentration was  $163.83 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DW}}^{-1}$  (RE = 81.5 %). Thus, during

PHASE 2 in R2 the antibiotic addition causes the effect of increasing the TPH removal with an effective bio-stimulating process, in accordance with the results observed microcosm tests.

At the beginning of PHASE 3, the liquid phase of both reactors was replaced with tap water in which NaCl was added to obtain the same conductivity present in the reactors at the end of PHASE 2.

In PHASE 3, TPH residual concentrations in both reactors increased although the residual concentration values remained lower than the initial values. In particular, this was likely to be the result of the release of TPHs sequestered by non-degraders (present in mixed cultures) or by other substances present in the bioflocs or biofilms structures (such as Extracellular Polymeric Substances or EPS) (Adav and Lee, 2008; Aksu, 2005). This phenomenon is one of the solid-liquid mass transfer mechanisms, typical of the slurry phase systems and is known as biological desorption. Despite the occurrence of TPH biosorption/desorption, residual concentration values remained lower than the initial values as it was, probably, effectively removed within the bioslurry system. In this novel setting, the R2 reactor still proved more efficient compared to R1. TPH concentrations are also evaluated in liquid phase in order to obtain a global mass balance.

In this experimentation, TPH concentrations in liquid phase have been measured on the 45<sup>th</sup>, 60<sup>th</sup> and 75<sup>th</sup> days of work. More specifically, the TPH measurements in the liquid phase were made only at the end of PHASE 2 and 3 (and in the intermediate period of PHASE 2). PHASE 1 was assumed to be similar (given the results on direct measurements of the solid phase). Therefore, only three measurements. This is due to the large volume required for the analysis, which would compromise the stationary condition of the two reactors.

At the end of each PHASE, the TPHs in the solution reached the values respectively of: 0.18 mg L<sup>-1</sup> (middle phase 2); 0.59 mg L<sup>-1</sup> and 0.42 mg L<sup>-1</sup> in R1; 0.18 mg L<sup>-1</sup> (middle phase 2); 0.58 mg L<sup>-1</sup> and 0.39 mg L<sup>-1</sup> in R2.

In a nutshell, TPH concentration in liquid phase increases (PHASE 2) when TPH concentration in sediment decreases, reaching concentration values of 0.59 mg L<sup>-1</sup> for R1 and 0.58 mg L<sup>-1</sup> for R2.

Subsequently, during the PHASE 3, TPH concentration values in the liquid phase decreased: until 0,42 mg L<sup>-1</sup> in R1 and; 0,39 mg L<sup>-1</sup> in R2. The results confirm the low variability between R1 and R2: probably, the bacteria in the liquid phase were able to quickly transform the TPHs into solution, and the general difference between the two reactors was due only to the phenomena involving the solid phase (desorption and interparticle biological transformations).

The results showed only a general correlation with the results obtained in the sediment phase: when TPH concentration in sediment decreases and, subsequently during the PHASE 3, TPH concentration values in the liquid phase decreased (following the “rebound” phenomena). The variations in TPH concentrations, between solid and liquid phase, depend on sorption and desorption phenomena. In order to study these phenomena, the main characteristics to consider are those related with the soil/water interface, such as the Specific Surface Area (SSA), the nature of the active sites available for adsorption (related for the type of adsorbent), and the pollutants nature (ionic, polar non-polar, amphiphilic). In addition, particle-related characteristics such as intra and interparticle porosity, particle size and tortuosity will also have to be considered.

The accumulation/utilization behavior of TPHs in the liquid phase, and their rebound effects, are diametrically opposed to the increase and present of TPH concentrations in the solid matrix, as observed in Figure 4.6

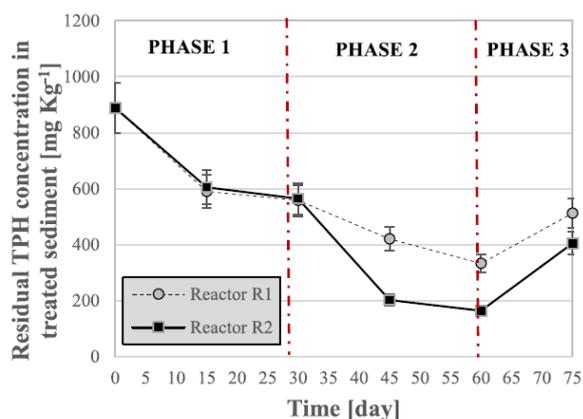
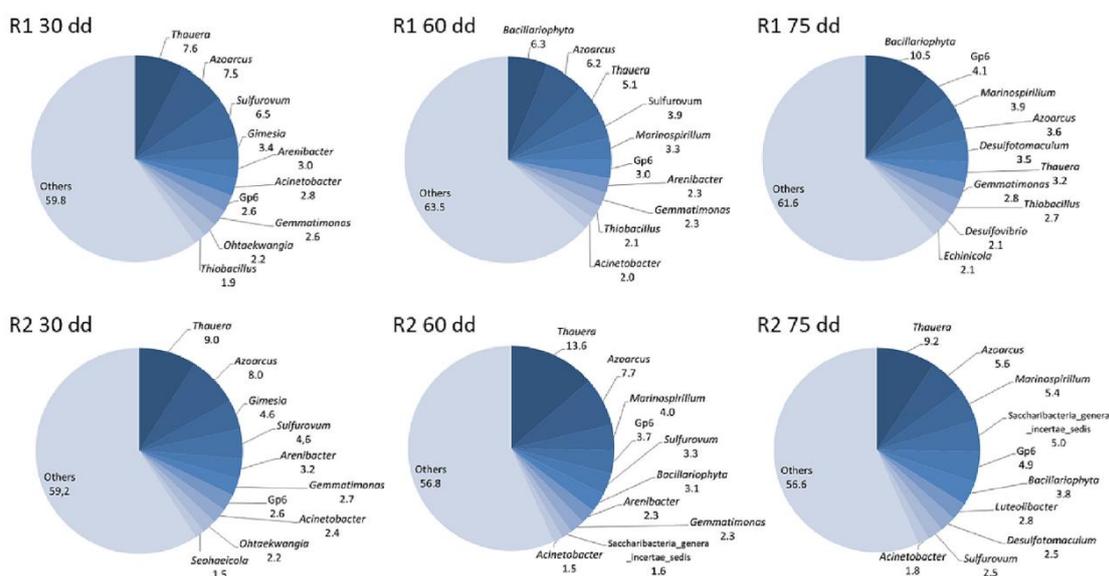


Figure 4.6 - TPH concentrations in different sediment phases (By Di Bella et al. 2023)

Finally, the results showed that the erythromycin allowed affecting the dynamic changes of microbial community structure during bioprocessing stages at the levels of both eukaryotic and procaryotic members. This results in an effect on the microbiome showing diverse hydrocarbon removal capability. In particular, based on microcosm tests, and with an erythromycin concentration dosage of to  $0.5 \mu\text{g mL}^{-1}$ , the bioslurry pilot plant confirmed that the presence of the antibiotic can select microbiota members having and optimized metabolism to remove TPHs. The presence of erythromycin, which constitutes a novelty in this topic area, underlined that further reduction of TPH concentrations can be promoted (biostimulated) thanks to the selection of more suitable microorganisms. Thus, this work showed that antibiotics could play a key role in microbiome modulation strategies for process improvement. Part of the results on microorganisms' abundance are shown in **Figure 4.7**



**Figure 4.7** - Relative abundance of the ten most abundant bacterial genera identified in R1 and R2 at the indicated days by NGS analysis of the V3-V4 region of the 16S rRNA encoding gene (By Di Bella et al. 20023)

However, this last aspect deserves further investigations to address different open critical aspects, including the problem related to antibiotics as emergent pollutants and their impacts on the spread of ARGs.

This last point implies the necessity of developing improved technological solutions to be applied to novel and advanced bioremediation systems.

## ➤ MAIN CONCLUSION

The results achieved during the project activities, which were carried out in an interdisciplinary way between **Task 4.5.2 and 4.5.3** of the RETURN projects, highlighted the important potential of the ex-situ bioremediation treatment.

The strengths are certainly linked to the satisfactory remediation performances achieved even on real sediments (Augusta and Genoa), with limited financial investments compared to other techniques.

The weaknesses are linked to the long treatment periods, not always predictable a priori. In this context, a "node" still unresolved, concerns the real contribution of specific bacteria (bioaugmentation and the stimulation of autochthonous ones (biostimulation)). For this reason, the treatment is among the least used on a real scale and complex contexts or realities.

The investigation, however, has inevitably contributed to the enrichment of the Scientific Know, and has indicated some critical nodes of technical and financial risk of the general applicability of bioslurry to sediments.

## Thermal Treatment: Thermal Desorption

### ➤ INTRODUCTION

With reference to physical remediation treatments aimed at sediment remediation, among the experimental research at laboratory scale, it is useful to show the research conducted in the field of the use of THERMAL DESORPTION. The study followed the results of different experiments carried-out with different batteries of tests: in particular, the experimentation concerned the applicability of the thermal treatment at low temperatures for the decontamination of contaminated marine sediments, whose results have been published in conference proceedings or are currently being published (accepted/submitted).

Among these we recall:

- [Licitra et al \(2024\) published as PROCEEDING on SIDISA 2024 XII International Symposium on Environmental Engineering Palermo, Italy, October 1 – 4, 2024](#)
- [Licitra et al \(2025\) submitted on Journal of Environmental Management](#)
- [Licitra et al \(2025\) published on Ingegneria dell'Ambiente Vol. 12 n. 2/2025](#)

The evaluation of remediation strategies to be implemented for the remediation of contaminated sediments must necessarily consider the possibility of reusing the matrix after treatment. In this sense, the reuse of marine sediments in construction materials is considered a sustainable alternative, especially when compared to their disposal in landfills ([Zhang et al., 2021](#)).

In general, the application of chemical or biological remediation technologies (such as sediment washing or bioremediation), is strongly dependent on the water content in the solid matrix to be treated. In fact, for bioremediation interventions, wet conditions are usually used to ensure better environmental conditions for microbial consortia, although a too high water content reduces the amount of soil/sediment that can be treated in the unit of time; in the case of soil/sediment washing, the use of high liquid/solid ratios generally leads to greater removal efficiency, but also a significant amount of washing solution ([Abbassi-Guendouz et al., 2012](#); [Trellu et al., 2016](#); [Zhao et al., 2019](#); [Zhang et al., 2021](#)).

In this context, it is also necessary to consider the contaminant load and its stability with respect to removal and therefore its persistence. In fact, while a limited contamination of hydrocarbons in the sediments (less than  $1500\text{-}2000 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DM}}^{-1}$ ), could be treated with alternative treatment techniques (chemical, physical or biological). At high concentrations (in the order of tens of thousands of  $\text{mg}_{\text{TPH}} \text{ kg}_{\text{DM}}^{-1}$ ), the useful, effective and convenient techniques are limited and strongly penalize biological remediation techniques (bacterial inhibition) and chemical processes (due to the high use of chemical additives) ([Ren et al., 2019](#); [Ahmed et al., 2022](#); [Song et al., 2024](#)).

In order to overcome these stringent critical issues, which do not allow the application in often-diversified conditions; thermal techniques seem to assume a particular interest, even if they are often characterized by high-energy consumption, which has always limited their use ([Zivdar et al., 2019](#); [Park et al., 2025](#)). Particularly, the application and treatment in different scenarios of contaminated sediment, Thermal Desorption (TD) is proposed as a particularly promising technology for sediment remediation. In recent years, in fact, it has aroused considerable interest, both from a scientific and operational point of view, thanks to its high removal efficiency and the reduced treatment times required. ([Zhao et al., 2019](#); [Bianco et al., 2020](#); [Wang et al., 2021](#)).

TD is a highly effective physical-thermal remediation technique for volatile and semi-volatile organic pollutants, but it must be kept in mind that the use of high temperatures involves the consumption of large amounts of energy and can compromise the properties of soils and sediments, modifying their ecological functions due to irreversible alteration of their mineral and chemical structure. For example, excessive heating can lead to the dehydration and decomposition of mineral clay lattice structures, kaolinite structures typically begin to break down when heated between  $420 \text{ }^{\circ}\text{C}$  and  $500 \text{ }^{\circ}\text{C}$ , so significant textural changes in soils and sediments due to heating are unlikely to occur at temperatures below  $400 \text{ }^{\circ}\text{C}$ . Thus, these disadvantages are, evidently, strictly related to the treatment temperature and duration of heating ([O'Brien et al., 2018](#); [Chen et](#)

al., 2024; Liao et al., 2024). In particular, several authors have referred to a temperature range between 300-350°C to define the treatment as Low Temperature Thermal Desorption (<300-350°C) or High Temperature Thermal Desorption (>300-350°C) (Falciglia et al., 2011; Liu et al., 2019; Li et al., 2020; Kristanti et al., 2022).

However, Low Temperature Indirect Thermal Desorption (LTITD) can be considered as a 'sustainable' remediation technology, thanks to energy savings (low temperature), maintenance of physical-chemical properties and rapid recolonization capacity of microbial communities in thermally treated soils and sediments. (Sang et al., 2021; Park et al., 2025).

Falciglia et al. (2020a) observed a slight decrease of marine sediments organic matter content when TD was applied in the range of low temperature (particularly, when temperature were less than 240°C). They also obtained high removal efficiencies applying LTTD for TPH's contaminated sediments, always greater than 80% when the treatment temperature was above 200°C (contact time of 20 minutes). Sang et al., 2021 obtained high removal efficiencies after treatment in the low temperature range to remediate lube-oil contaminated matrices. The LTTD application at a temperature of 350°C was 94% effective.

Li et al. (2020) analyzed the mineralogical structure of the petroleum contaminated solid matrix after TD both at low temperatures and at high temperatures, highlighting some minerals decomposing such as carbonate salt at temperatures above 500°C. High Temperature Thermal Desorption also were investigated for physicochemical properties, demonstrating that the heating process can significantly reduce organic matter and total nitrogen content.

Furthermore, from a management point of view, the organic contaminants desorbed/volatilized during the thermal treatment make it necessary to prepare appropriate management and treatment systems for off-gases (in the form of VOCs, Volatile or semi-volatile Organic Compounds), useful for preventing secondary contamination phenomena, due to the emission of such pollutants into the atmosphere (Zhao et al., 2019; Kristanti et al., 2022). However, despite the potential advantages, very few applications of TD at low temperatures have been reported in the literature so far, and even fewer with specific reference to contaminated sediments.

In this context, the experimental study object of this activity investigates the effectiveness of LTITD, against marine sediments contaminated by hydrocarbons. In particular, the experimental analysis involved the investigation of the results obtained with a laboratory-scale TD plant for the treatment of three different contaminated matrices at different initial concentrations (low, medium and high), at different temperatures and different contact times.

Finally, the effect of a possible adsorption treatment on the off-gas produced was evaluated, using innovative recovery matrices (BIOCHAR) and commercial matrices (GAC, Granular Activated Carbon), in order to propose a simple and environmentally compatible technique for controlling gaseous discharges, and to demonstrate that the re-use of these adsorbent materials is an innovative alternative to activated carbons.

The results were discussed comprehensively, considering both the priority object of study (decontamination of marine sediments) and the design and management aspects (including energy consumption and off-gas control).

## ➤ MATERIALS AND METHODS

The marine sediments, object of the present study, were collected from Sicilian port areas and have been already subjected to previous studies (Lumia et al., 2020 a,b; Avona et al., 2022), similarly to previous sediment discussed above. In particular, the real matrix (obtained by mixing different real samples stored in a cold room) presented a residual hydrocarbon contamination slightly higher than  $\text{mg}_{\text{TPH}} \text{kg}_{\text{DM}}^{-1}$  (real residual contamination of  $787 \text{ mg}_{\text{TPH}} \text{kg}_{\text{DM}}^{-1}$ , however higher compared to the Regulation limit for "sites for commercial and industrial use"). To evaluate the effectiveness of TD for the treatments of polluted sediments, at low-medium and high contamination condition, it was decided to artificially contaminate the available sediments, by adding commercial diesel, in order to guarantee a significant TPH contamination for the investigation.

Specifically, the contamination was carried out in three distinct phases, by adding a known volume of commercial diesel (C13-C25), and a subsequent stirring phase, using a digital shaker "VWR Advanced Digital Shaker" for a given contact time. In particular, the sediment/diesel ratio of 500 g/80 mL (first contamination)

and 500 g/500 mL (second contamination) and 500 g/250 mL (third contamination) was used. The sediments thus contaminated were stirred at a speed of 150 rpm for 60 days. Once the mixing phase was completed, a filtration phase was carried out to remove the non-adsorbed diesel layer from the sediments.

The experimental campaign was planned based on the results obtained from the treatment of the first two artificially contaminated matrices (first and second contamination, respectively with low and high level of contamination). Subsequently, based on the chemical and energetic evaluations of efficiency, we proceeded to the experimental analysis of an intermediate contamination level (third contamination), which also justified the use of a thermal treatment rather than a biological or chemical one (the same matrix was used for parallel experimental campaigns on the chemical-biological treatment of sediments).

The specifications and operating conditions of experiments are reported in the next paragraph. [Table 4.2](#) reports the initial characterization of the artificially contaminated sediments in the various experimental steps hypothesized, including also the water content of sediments entering the thermal desorption unit.

**Table 4.2** Initial characterization of artificially contaminated sediments

<b>First contamination</b>		
Sediment mass	500	g
Total Volume of Diesel	80	mL
TPH	<b>1336</b>	mg <sub>TPH</sub> /kg <sub>DM</sub>
Moisture	11.6	%
<b>Second contamination</b>		
Sediment mass	500	g
Total Volume of Diesel	500	mL
TPH	<b>35011</b>	mg <sub>TPH</sub> /kg <sub>DM</sub>
Moisture	14.2	%
<b>Third contamination</b>		
Sediment mass	500	g
Total Volume of Diesel	250	ml
TPH	<b>13182</b>	mg <sub>TPH</sub> /kg <sub>DM</sub>
Moisture	12.6	%

The experimental work was developed in three phases, namely PHASE 1, PHASE 2 and PHASE 3. In the first two phases the performances of the TD were compared as a function of the initial concentration of contamination, evaluating the effects of the oven temperature (PHASE 1) and the sediment/heat source contact time (PHASE 2), for both contamination levels (first and second contamination).

Once the optimal process parameters for the remediation of the contaminated matrix (temperature and contact time) were identified, the off-gas control analysis was carried out (PHASE 3) evaluating the adsorption capacity of the absorbent material used to prevent atmospheric pollution phenomena. In this case, as discussed above, it was decided to proceed adopting an artificially contaminated matrix, different from the first two phases, but with the optimal process parameters obtained from the first two. The treatment of the contaminated matrix in the third contamination step involved 3 tests (P1-P2-P3) carried out with the same (best) operating conditions of LTITD but with 3 different adsorbent materials on the off-gas circuit: a commercial activated carbon (GAC) and two different types of BIOCHAR (1 and 2).

[Table 4.3](#) summarizes the operating conditions used in each single experimental phase. The selection of these factors and their experimental levels was based on previous studies ([Falciglia et al., 2011](#); [Liu et al., 2019](#); [Falciglia et al., 2020a](#); [Sang et al., 2021](#)).

Table 4.3 Operating conditions during the three experimental phases

EXPERIMENTAL PHASE	SEDIMENT MASS	TEMPERATURE	TIME OF CONTACT	GAS LINE
PHASE 1	20 g	200°C	15 min	trap
		350°C		
		500°C		
PHASE 2	20 g	200°C	10 min	trap
			15 min	
			20 min	
PHASE 3	20 g	200°C	15 min	GAC + trap
				BIOCHAR 1 + trap
				BIOCHAR 2 + trap

Specifically, as described above, the thermal desorption tests carried out in the first two phases concerned the optimization of the two main operating parameters: in PHASE 1, thermal desorption treatments were conducted at different temperatures; in PHASE 2, different desorption times from the solid matrix were studied while maintaining the optimal temperature identified during the first experimental phase constant.

Referring to Table 4.2 and the operating ramps of the pilot plant, described in detail in the next paragraph, the first three tests were carried out at the maximum temperature of 200, 350 and 500°C and a contact time of 15 minutes. Subsequently, three further tests were performed, in which the contact time was varied to 10, 15 and 20 minutes while maintaining the optimal maximum process temperature detected by the first tests (equal to 200°C). Furthermore, during tests execution, the energy consumption required was monitored via a digital wattmeter.

Finally, once the optimal parameters were set, on the basis of the previous phases, the treatment efficiency was evaluated on the sediment with an average TPH contamination while evaluating the treatment efficiency of the off-gas by three different adsorbent materials according to the repetition of three tests (P1-P2-P3) conducted with the same LTITD conditions.

The experimental apparatus used to simulate Thermal Desorption, installed at the Energy and Environment Laboratory of the University of Enna "Kore" and shown in Figure 4.8.



Figure 4.8 - Experimental set-up SAFTherm SANTE FURNACE with 60 mm diameter quartz tube

The system consists of a tubular furnace of the type (Split Furnace) with heating elements "SAFTherm SANTE FURNACE", equipped with a quartz tube of 60 mm diameter and 800 mm long. The Split Furnace was equipped at the ends with gastight stainless-steel flanges for the control of the internal atmosphere and the

flushing of specific carrier gases (typically inert gases such as nitrogen) which allowed on the one hand the maintenance of a controlled atmosphere and on the other hand the removal of the desorbed fumes and vapors.

The sediment samples (approx. 20.0 g of grain size < 2 mm and previously dried in an oven at 40°C for 48 hours, thus reaching the water content shown in Table 4.2) were placed in the middle of the tube inside a quartz boat. From one end of the quartz tube, the carrier gas (nitrogen) was fluxed at a constant flow rate of 1.5 L/min in order to keep an inert atmosphere inside the tube. The opposite end of the quartz tube was appropriately connected to an off-gas recovery system, consisting of two cryogenic traps for the condensation of VOCs (maintained at a temperature of 4°C, with a water and ice bath), containing a known volume of iso-propanol.

During PHASE 3, columns packed with adsorbent material were added to the traps, already used in the previous phases. The traps were placed in series with the adsorption columns. The flow diagram of the treatment system, from the transport carrier to the off-gas measurement and control system is shown in Figure 4.9.

### TEST – PHASE 1 and 2



### TEST – PHASE 3

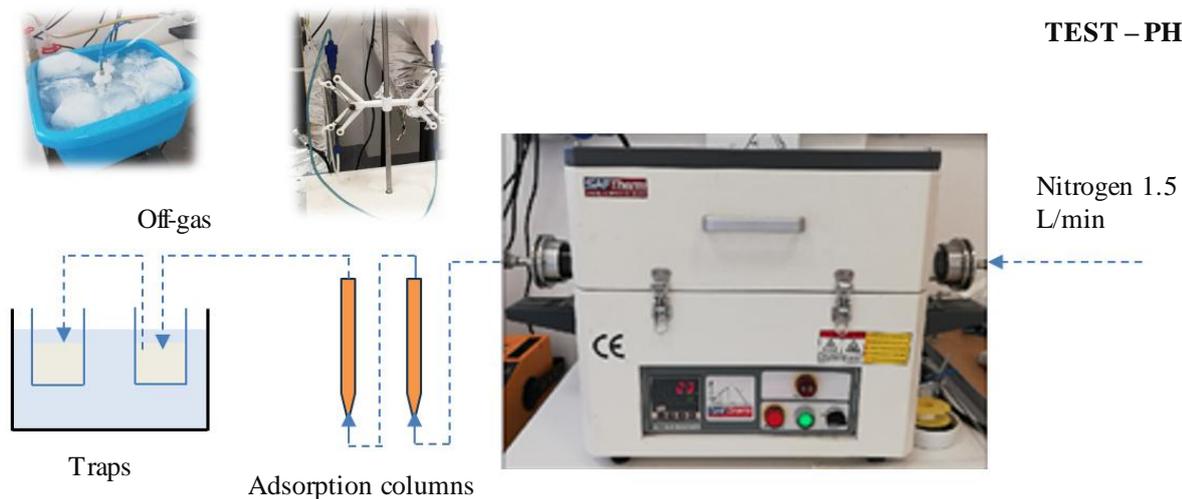


Figure 4.9 - Representative diagram of the pilot plant, connected downstream with the off-gas management system

Each TD test was performed by setting specific heating ramps, i.e. individual work steps (setting heating times and temperatures) of the tubular furnace for the volatilization of TPH contained in the sediments. In general, the work steps considered were the following:

- heating from room temperature to 105°C for the removal of residual humidity;
- constant maintenance of the drying temperature at 105°C for 20 minutes;
- heating up to the maximum design temperature expected for each test, to be reached in 5 minutes;
- maintenance of the maximum design temperature for the pre-established desorption time;
- interruption of heating once the design desorption time at the maximum temperature has elapsed.

The heating ramps for the PHASE 1, 2 and 3 tests are shown in Figure 4.10 a-c.

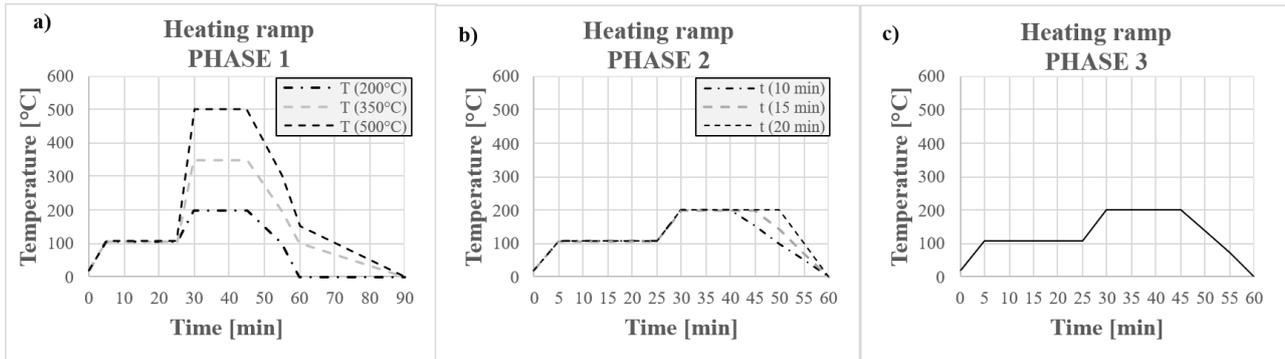


Figure 4.10 - a) Heating ramps as the temperature varies (PHASE 1); b) heating ramps as the contact times vary (PHASE 2) c) heating ramp for adsorbent material tests (PHASE 3).

Finally, the characteristics of some adsorbent materials and management of off-gases were also studied

The University of Palermo provided the biochars used for the adsorption of off-gases following the thermal treatment. The two types of BIOCHAR, obtained from the pyrolysis of tree species such as pine and eucalyptus (Figure 4.11), called B440 and B880, presented different characteristics (Table 4.4), starting from their granulometry. In fact, B440 was characterized by particles with smaller dimensions than B880, which was made up of particles with a more rounded and coarse shape (>2mm).

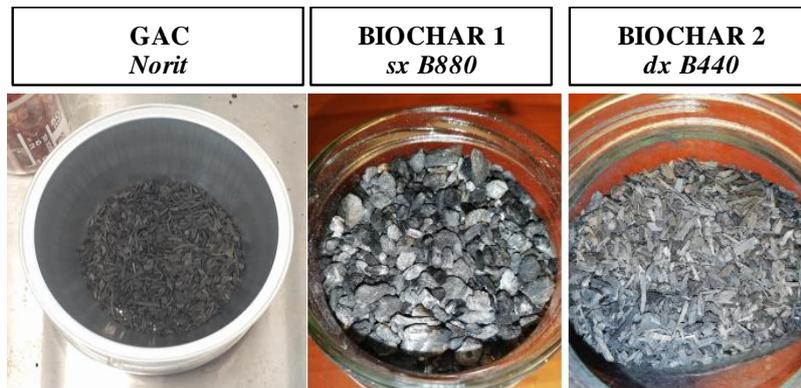


Figure 4.11 - Adsorbent material used for adsorption columns (P1-P3)

Table 4.4 Characteristics of the two types of biochar and of the GAC being tested

Parameters	U.M.	GAC (Norit)	B880	B440
pH	-	8	10	9
moisture	%	3.9	6.7	3.1
bulk density	g/L	176	63	125
Total pore volume	cm <sup>3</sup> /g	95	51	38
Surface area	m <sup>2</sup> /g	279	227	164
Electric conductivity	dS/m	/	2.0	1.3
Ashes at 550°C	%	8	6.4	3.4
Total carbon (TC)	%	/	72	65
Total nitrogen (TN)	%	/	0.3	0.3

In order to prevent air pollution phenomena, due to the dispersion of pollutants volatilized by the sediments, a system consisting of two Pyrex adsorption columns placed in series and a cold trap (-30°C). Trap containing ethanol was set up at the outlet of the quartz tube, with the aim of separating the desorbed compounds through physical adsorption and condensation processes.

The columns, characterized by a net volume of approximately 0.35 L, were filled with GAC in test P1 and with BIOCHAR in tests P2 and P3. The columns were completely packed to fill the entire available volume (with variable masses of the adsorbent, depending on the individual specific density). Considering the different dimensional characteristics of the tested adsorption materials, the columns filled with activated carbons (P1) contained (both) approximately 6.0 g, while during the tests conducted with BIOCHAR the columns contained 4.5 g of B440 (P2) and approximately 2.0 g for B880 (P3).

To determine the effectiveness of thermal desorption experiments and the surface functionalities for B440 and B880, FTIR analysis was carried out using a Shimadzu IR Tracer spectrometer in mid-IR mode, equipped with a Universal ATR sampling device containing diamond/ZnSe crystal. The spectra were recorded in the range from 600 to 4000 1/cm, with a resolution of 4 1/cm, by averaging 64 scans, spectra were baseline corrected and normalized.

### ➤ MAIN RESULTS

As previously observed, the experimental investigation was developed with two investigation approaches.

The first experimental approach, carried out on the basis of the tests conducted in PHASE 1 and 2, aimed at verifying the impact of the process temperature and contact times, with tests carried out with an initial TPH concentration of 1335 mg kg<sub>DM</sub><sup>-1</sup> (limited contamination) and 35011 mg kg<sub>DM</sub><sup>-1</sup> (significant contamination).

The second approach, instead, was aimed at comparing the effects of the reduction of pollutants in exhaust gases. In this case, in order to extend the results of the investigation, confirming the data obtained from the previous investigation PHASES, it was decided to operate with the best process conditions and with an intermediate contamination of the sediments, equal to 13182 mg kg<sub>DM</sub><sup>-1</sup>

The in-depth analysis of the results was developed over several phases and different batch tests. The results relating to each individual experimental phase are discussed in the paragraphs below.

### ➤ PHASE 1: experiments at different temperatures

Following the first contamination of the sediments, three TD tests were conducted by varying the maximum temperature reached during the treatment. In particular, the setting of the heating ramps provided for an initial drying phase inside the furnace at 105°C with a nitrogen flow to guarantee an inert atmosphere inside the quartz tube and the subsequent reaching of the maximum treatment temperature, respectively equal to 200, 350 and 500°C for a contact time of 15 minutes. The results obtained from the analysis of the residual concentration of TPH in the sediments following the first three tests, reported in [Figure 4.12](#). Data highlighted a very high effectiveness of the treatment starting from the test conducted at a maximum temperature of 200°C, following which compliance with the CSC imposed by the legislation was guaranteed, the residual concentration of TPH being equal to 16.2 mg kg<sub>DM</sub><sup>-1</sup>. Finally, the tests carried out at 350 and 500°C showed the complete removal of hydrocarbons from the contaminated matrix with removal efficiency of 99.96 and 100%, respectively.

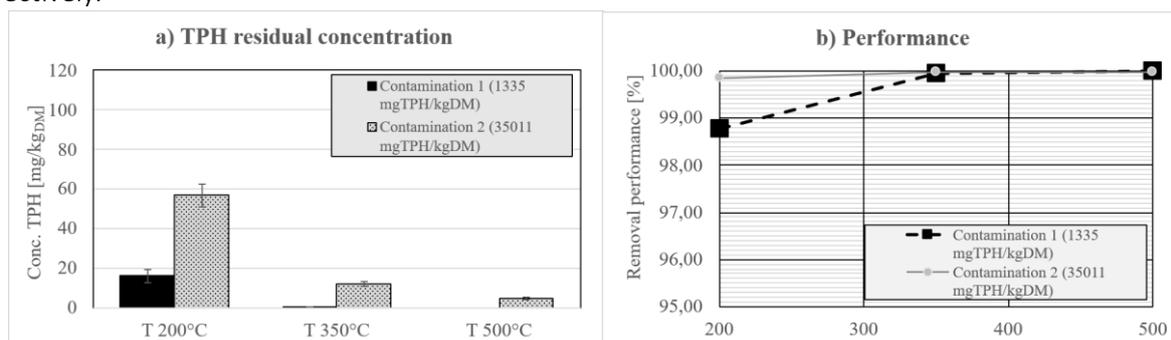


Figure 4.12 - Residual concentration (a) and removal efficiencies (b) of TPH as a function of TD temperature for the first and second contamination

The tests, with the three different temperature ramps, were repeated for the second contaminated matrix at high concentrations: about 35000 mg/kgDM. In addition, in this case, the yields were more than satisfactory:

- a yield of 99% was obtained at the working temperature of 350 and 500°C;
- 81% of TPH removal was achieved with the residual concentration of TPH equal to 57 mg kg<sub>DM</sub><sup>-1</sup> at 200°C;
- in the last case, despite the high removal percentages, the limits relating to COLUMN A of Legislative Decree n. 152/2006, part IV, Table 1, and Annex 5 were slightly exceeded (50 mg kg<sub>DM</sub><sup>-1</sup>). Conversely, the limits were respected when higher temperatures were applied: 12 and 5 mg kg<sub>DM</sub><sup>-1</sup>, respectively at 350°C and 500°C).

### ➤ PHASE 2: experiments at different contact times

From the results achieved in PHASE 1, three further TD tests were performed in which the desorption time was varied in an inert atmosphere when the process temperature was kept constant. In more detail, the tests were carried out with contact times of 10, 15 and 20 minutes at a process temperature of 200°C. From the analysis of the residual concentration of TPH in the treated sediments, it emerged that the limits set by the current legislation relating to COLUMN B of Italian Legislative Decree 152/2006, part IV, Table 1, Annex 5 had been reached, for all condition and both sample of contaminated sediment.

On the contrary, with regards to the limits of COLUMN A, despite the high percentage yields (greater than 99.8%), the residual concentration after treatment of the highly contaminated matrix (35011 mg kg<sub>DM</sub><sup>-1</sup>) was:

- satisfactory and compliant with Regulation limits, for the tests conducted over 20 minutes (37 mg kg<sub>DM</sub><sup>-1</sup>);
- slightly higher than the limits for the test conducted at 15 minutes (50.9 mg kg<sub>DM</sub><sup>-1</sup>);
- significantly higher for the test conducted at 10 minutes (92.0 mg kg<sub>DM</sub><sup>-1</sup>).

Figure 4.13 summarizes all the data and results of PHASE 2.

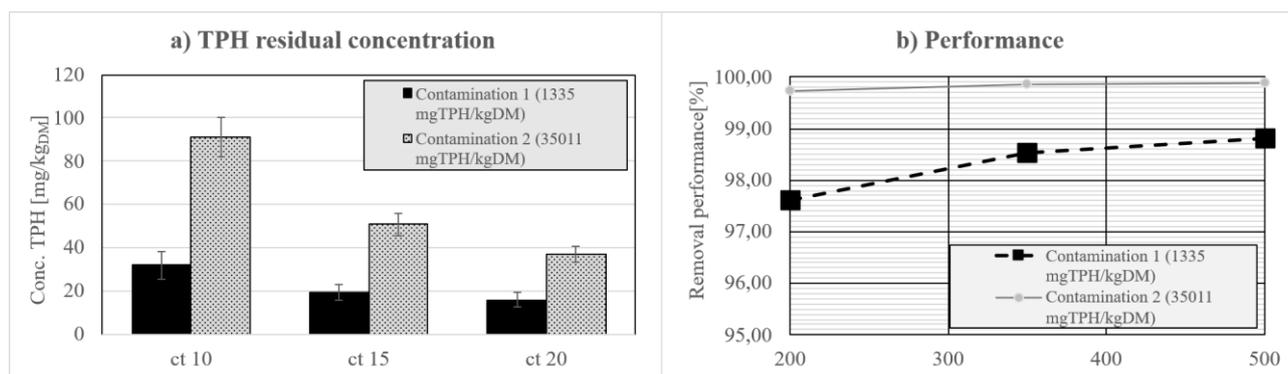


Figure 4.13 - Residual concentration (a) and removal efficiencies (b) of TPH as a function of the contact time of TD for the first and second contamination

The removal efficiencies obtained in PHASES 1 and 2 were consistently high, despite the difference in initial TPH concentration in the sediments following the two distinct contamination phases. Concerning the residual conditions, despite the significant efficiencies, but in light of the more restrictive Regulation limits, the best working scenario can be assumed the one characterized by a working temperature of 200°C and a contact time of 15 minutes for initial TPH concentrations lower than 30000 mg kg<sub>DM</sub><sup>-1</sup>.

The result is also confirmed by the double repeatability carried out in the tests of the two phases: from the initial 35000 mg kg<sub>DM</sub><sup>-1</sup> in the original matrix, the residual value of TPH in the treated sample was equal to 57 and 51 mg kg<sub>DM</sub><sup>-1</sup>, in PHASE 1 and 2 respectively (at ct = 15 minutes and Temperature of 200°C).

➤ PHASE 3: vapor adsorption tests by varying the adsorbent material

The need to prevent uncontrolled emissions of VOCs desorbed into the atmosphere led to the need to preliminarily evaluate the characterization of the potential off-gas produced. In this sense, an appropriate management system was set up at laboratory scale, already discussed above. A typical composition of the exhaust gases produced by the TD tests is reported in Figure 4.14, in terms of VOC concentration, measured during the test performed at the maximum temperature of 200°C (optimal temperature condition) and with a contact time of 15 minutes. From the analysis of the chromatograms, it was possible to detect the presence of TPH in both traps (placed in series), in line with expectations: in greater quantities for the first trap; smaller but not zero for the second. The general scenario demonstrates the need for further investigations aimed at identifying a complementary and closed system to be able to manage all the off-gases desorbed from the sediments. In this sense, and as previously introduced, two different off-gas treatment systems were tested:

- activated carbon adsorption systems;
- adsorption systems using different biochars obtained from the pyrolysis of residual organic waste.

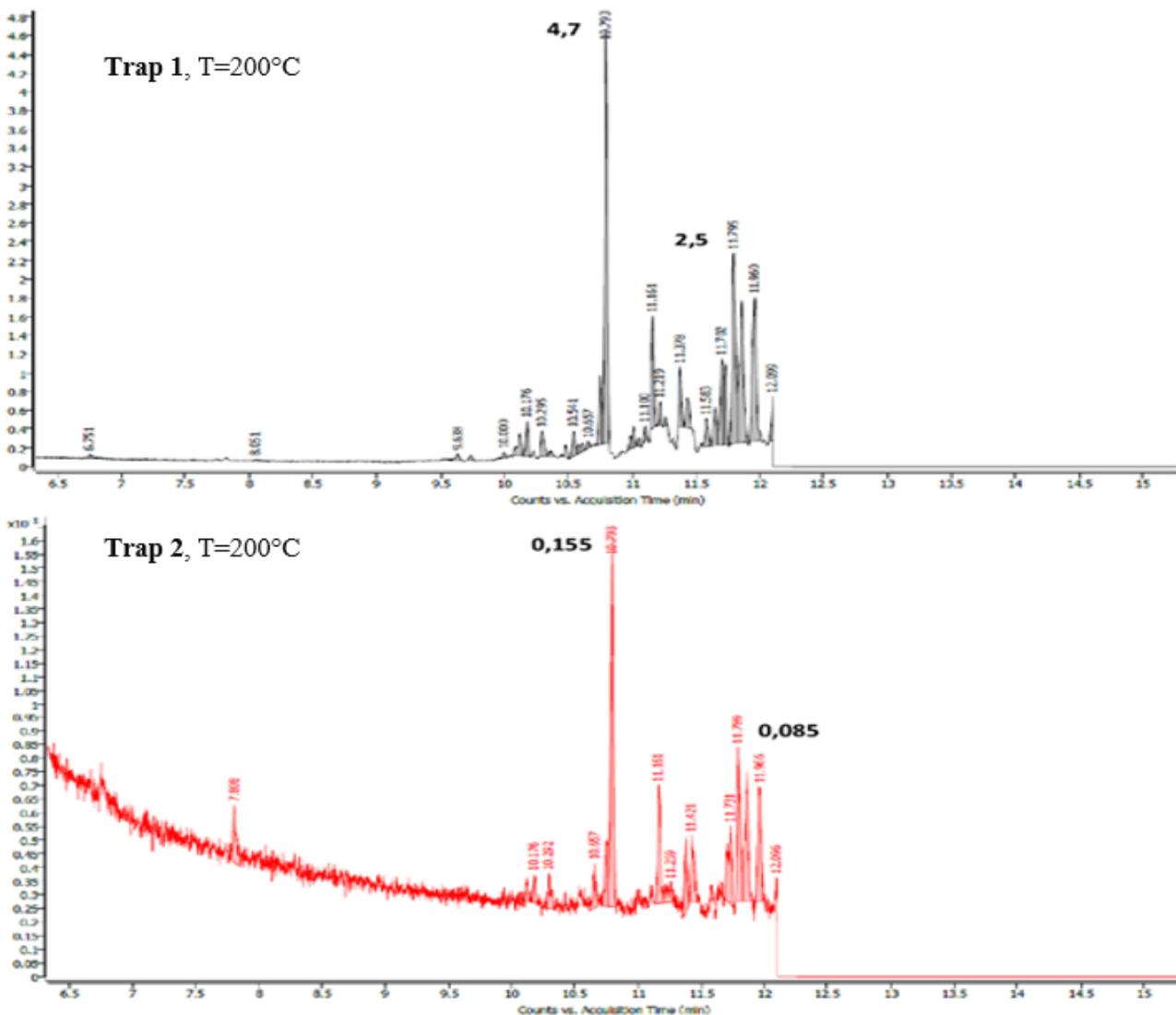


Figure 4.14 - Chromatograms of the chemical compounds recovered in the two traps taken following the test at T=200 °C and tc=15 min.

It is useful to underline that all three tests conducted at working temperature at 200°C and with a contact time of 15 minutes in PHASE 3, confirmed the results, and the repeatability of the test, previously observed in PHASE 1 and 2:

- residual concentration of TPH in the sediments  $17 \pm 2 \text{ mg kg}_{\text{DM}}^{-1}$ ;
- average desorption efficiency equal to 99.8%.

The decontamination process allowed reducing all pollutants and obtaining treated sediments potentially reusable according to the law.

As regards the control of off gases, the study was based on the measurement of a general and inclusive parameter: being a totally closed system, consisting of the emission source directly connected to the adsorption treatment (on two columns) and to the final condensation traps, the collected gas was adsorbed in the biochar or trapped entirely. In this context, and in this experimental phase, the preliminary analysis was based on the measurement of TPH adsorbed directly in the studied matrices (Norit, B8880 and B440) and condensed in the final traps.

The tests have shown that the system consisting of the series of adsorption columns and cold traps is very efficient, especially when B880 is used as an adsorbent material. In fact, from the evaluation of the concentration of adsorbed TPH, carried out for the two columns of each adsorbent material tested, the high adsorption efficiency of BIOCHAR B880 emerged. The adsorption performance was equal to an average of 78% of the pollutants desorbed from the sediments, a value close to the 83% observed in the case of commercial activated carbons (Figure 15a).

On the other hand, BIOCHAR B440 performed the worst, with an average adsorption of about 67%.

In general, adsorption was distributed homogeneously between the first and second columns, with a slight prevalence for the second column in the case of NORIT and B440, and in the first column in the case of B880. The differences are generally considered to be the effect of the type of experimental setup (bench-scale) rather than due to the effects of packing due to differences in density or intrinsic characteristics.

Figure 15b, comparing the adsorption in terms of TPH mass per mass of adsorbent material, shows that the abatement potential of BIOCHAR is actually significantly higher than what the simple abatement percentages show. In this sense, the figure shows that the specific adsorption efficiency of B880 is higher than that of B440 which is higher than the commercial NORIT activated carbon with values of 43, 18 and mg TPH/mg Adsorbent respectively. On the contrary, in terms of TPH adsorbed per volume of adsorbent the values are very similar ( $2 \pm 0.1$ ) mg TPH  $\text{cm}^{-3}$ ): this condition is undoubtedly due to the different density of the adsorbent materials which, at least in terms of volume of adsorbent, mitigates the differences in volumetric adsorption.

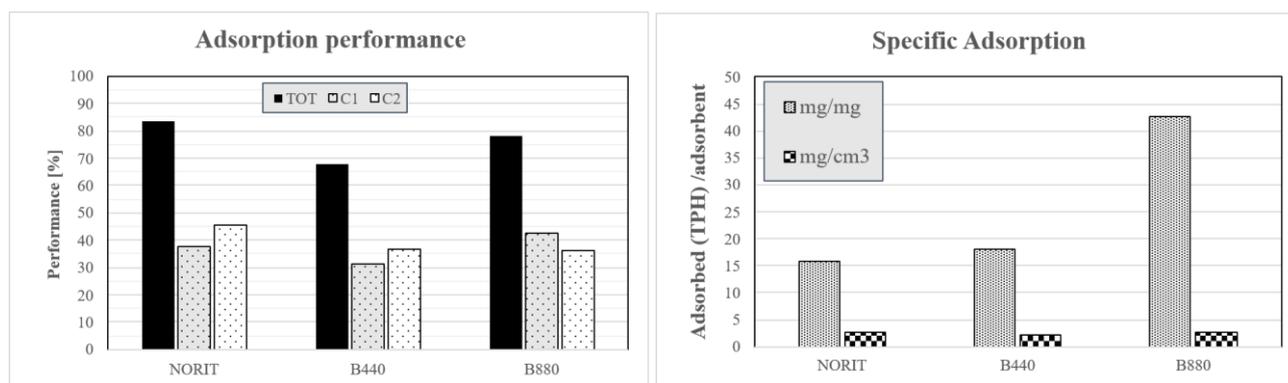


Figure 4.15 - Efficiency (a) and specific adsorption per unit mass and volume (b) of the adsorption columns and the trap

Despite the interesting results, considering the important contamination status of the solid matrix, the adsorption system was not effective enough to recover all the TPH desorbed during heating. In fact, a significant percentage (which varies between 25 and 40%, approximately) was recovered inside the cold trap at the end of the circuit.

Nevertheless, it is believed that the use of recycled BIOCHAR is a very useful alternative to commercial adsorbents, both in terms of treatment efficiency and in relation to the purposes of the circular economy.

### ➤ Comparison between the different TD tests and general considerations

The analysis of the results discussed in the previous paragraphs highlights how in general longer contact times and higher temperatures guarantee the total removal of TPH. Obviously, as previously stated, the most suitable operating conditions for a real-scale application are those that guarantee the achievement of the remediation objectives (compliance with the Regulation limits) with the least economic commitment, both for

investment and for operating costs. Therefore, the optimal operating condition of the process is the one that involved the thermal desorption of the sediments conducted at 200°C for at least 15 minutes.

Together with the study of the process efficiencies, a preliminary analysis was carried out of the applicability of a system for the reduction of hydrocarbons present in the exhaust gases (off-gas) produced by the process. The scientific analysis stimulates and directs future research on the application of adsorbent materials from dry and/or wet pyrolysis treatments of organic waste, which would thus find their use in the field of environmental recovery of polluted matrices such as those of marine sediments of port areas subjected to intense human activities.

In this context, the BIOCHARs used both show high potential as adsorbent agents. These applications, extremely interesting, certainly require further investigation to determine the optimal amount of adsorbent necessary for the complete abatement of pollutants, the speciation of TPH and direct measurements of VOCs in the gas flow at each point of the circuit of the fume treatment line, potentially assessable by detector (FID, Flame Ionization Detector or PID, Photoionization Detector). To improve system closure and the complete recovery of VOC, some strategies could be implemented, including a system consisting of adsorption columns with larger volume, thus increasing the mass of adsorbent material to be introduced, followed by an increased number of condensing traps.

To corroborate what has been analyzed so far, the analysis of the energy consumption of the plant is undoubtedly particularly useful. Although conducted at laboratory scale, the study can provide useful information regarding energy savings for a possible process scale-up, especially with reference to the relative comparison, rather than the absolute data, of consumption between the different operating conditions analyzed in this study.

For the evaluation of energy consumption, during the individual tests conducted in the laboratory, a digital wattmeter was used, which allowed to calculate the electrical and thermal energy consumed for the volatilization of TPH as a function of the mass of sediment treated. As can be seen from the relative comparison of the consumptions reported in [Table 4.5a](#), the energy consumption was equal to 3.75 kWh/kg SEDIMENT for the thermal desorption test carried out at the maximum process temperature of 500°C and 20 minutes of contact time. At lower working temperatures and equal treatment times, the consumption was reduced by about a third at 350°C (2.67 kWh/kg SEDIMENT) and by almost 60% at 200 °C (1.59 kWh/kg SEDIMENT).

Once the optimal working temperature (200°C) was defined, corroborated by the removal efficiency data described in the previous parameters, we moved on to the consumption analysis considering a reduction in contact times. In this case, as reported in [Table 4.5b](#), a further saving of 14.2% is obtained with a  $t_c=15$  minutes (1.37 kWh/kg) and a further 27.1% at  $T_c=10$  minutes (1.16 kWh/kg).

These results showed the convenience of applying physical-thermal technology using low temperatures which allowed to obtain satisfactory yields even if slightly lower than those obtained at high temperatures (350 and 500°C) and guarantee a reduction in energy consumption equal to 40-70% compared to applications at medium-high temperatures.

In particular, considering the average cost of energy (for industrial applications) at the time of the investigation (0.23 €/kWh + VAT), one can imagine a treatment of sediments contaminated with LTTD at 200°C that varies between 325 and 383 €/t with a process conducted respectively at 10 or 15 minutes of contact time, against over 1000 €/t of a TD treatment conducted at 500°C and 20 minutes of contact time.

**Table 4.5** Energy consumption by varying the process temperature; b) energy consumption by varying the contact time at 200 °C

a) Consumption reduction with T [%], 20 min			b) Consumption reduction with $t_c$ [%], 200 °C		
$T_{max}$ [°C]	$C_e$ [kWh/kg]	$\Delta C_e$ [%]	$t_c$ [min]	$C_e$ [kWh/kg]	$\Delta C_e$ [%]
500	3.75	-	20	1,9	-
350	2.67	28.75	15	1.37	14.20
200	1.59	57.46	10	1.16	27.14

## ➤ MAIN CONCLUSION

The results achieved during the project activities, which were carried out specifically in **task 4.5.3** of the RETURN project, highlighted the important potential of the ex-situ remediation treatment. The results obtained confirmed that thermal desorption is indeed a feasible technology for the remediation of sediments contaminated by organic pollutants, even at low temperatures (200°C).

Specifically, the TD tests carried out on samples of contaminated marine sediments showed a high efficacy of the treatment for the removal of TPH in all the tests carried out, with removal efficiencies varying between 98 and 100%. The results obtained clearly show the scientific interest of applying the treatment at low temperatures, significantly lower than those of thermal destruction (> 600°C). Furthermore, thermal solution at high temperature would lead on the one hand to an increase in energy consumption (therefore costs) and on the other to the progressive deterioration of the properties of the sediments and therefore fewer management solutions aimed at reusing the remediated environmental matrix.

The general evaluated process parameters allowed identifying as optimal values a contact time of 15 minutes and a maximum process temperature of 200 °C. The contact time could also be reduced to 10 minutes in less demanding regulatory scenarios (reuse in industrial areas). Based on these applications, energy consumption can be reduced by up to 70%, promoting the diffusivity of the process also for the treatment of contaminated marine sediments (as well as soils).

Finally, in order to delve deeper into the aspects related to the sustainable treatment of off-gas, the study proposes the use of BIOCHAR of pyrolysis from organic waste materials, rather than the use of expensive, and often less efficient, commercial adsorbent materials.

However, in view of full-scale applications and for the purpose of reusing, the eco-toxicity of sediments after treatment (e.g. bioassays with benthic organisms) should be thoroughly investigated, in order to ensure ecological safety for marine reuse.

Similarly, the results on the effect referred to some particularly impactful organic pollutants, such as mercury, should be further investigated.

Finally, technological growth, the combined use of new "furnaces" and "series" treatment, could reduce energy costs. In this sense, an excellent possibility of energy optimization could be addressed to the coupling of thermal treatment technology and renewable sources (for example, solar condensers ...).

## CHEMICAL TREATMENT: SEDIMENT WASHING

### ➤ INTRODUCTION

The experimental in-depth study in the field of physical-chemical treatments aimed at sediment remediation, was approached on the basis of past investigations and experiments conducted by the research groups involved (particularly, UKE-UNIPA), which can be found in the literature.

In particular, in **Task 4.5.3**, the experimental campaigns focused their attention on the use of specific chemicals such as "surfactants" and "oxidants", which are little used and reported in the literature. In this sense, it was decided to propose further research advances on the basis of less general and more "advanced" "themes" in the use of products potentially useful for sediment washing.

Results have been published in conference proceedings or are currently being published (accepted). Among these we recall:

- [Russo Tiesi et al. \(2024\). published as PROCEEDING on SIDISA 2024 XII International Symposium on Environmental Engineering Palermo, Italy, October 1 – 4, 2024](#)
- [De Marines et al. \(2025\). Published as PROCEEDING on SiCon 2025 Workshop su: Siti Contaminati. Esperienze negli interventi di risanamento](#)
- [Russo Tiesi et al. \(2025\). Published as PROCEEDING on SiCon 2025 Workshop su: Siti Contaminati. Esperienze negli interventi di risanamento](#)
- [Russo Tiesi et al \(2025\) published in Journal of Environmental Chemical Engineering](#)

Among the proposed technologies for sediment reclamation, Sediment Washing (SW) represents a promising ex-situ treatment, where pollutants are extracted from sediments by means of a washing solution, eventually augmented with chemicals. Therefore, contaminants are transferred from the sediment to the solution and subsequently removed (Lumia et al., 2020a).

Referring to petroleum hydrocarbons, literature studies revealed that surfactants play a crucial role since they can enhance the mobilization and dissolution of oil contaminants into water through the reduction of air/water surface tension, oil/water interfacial tension, and micellar solubilization (Liu et al., 2021; Shih et al., 2020).

Sediment washing can achieve high removal efficiencies, limiting the deterioration of physical-chemical properties of sediment and microbial activity while leading to reduced operating costs (Lumia et al., 2020a). Surfactants are amphiphilic molecules composed of a hydrophilic head and hydrophobic tail; they can have natural origins, e.g., derived from plants or microorganisms, or can be artificially synthesized. When surfactant molecules are at low concentrations, they are dispersed in solution as monomers. As the concentration of surfactant increases, they begin to aggregate into micelles, driven by the mutual attraction of hydrophobic groups.

The concentration threshold at and beyond which micelles form is the critical micelle concentration (CMC), which varies for each surfactant. Generally, the solubilization of oil contaminants is not effective until the CMC is exceeded (Liu et al., 2021). CMC varies among surfactants, and a lower value indicates that more micelles will form at the same surfactant concentration. Over the last years, Tween 80 and Sodium dodecylbenzene sulfonate (SDBS) are among the surfactants that have aroused significant interest in removing petroleum hydrocarbons. In particular, Tween 80 is a non-ionic surfactant. Non-ionic surfactants are not ionized and do not have charge; noteworthy, the monomers of non-ionic surfactants aggregate more easily to form micelles thanks to the absence of a repulsive effect between monomers. Thus, they usually have a lower CMC than other surfactant categories, such as anionic and cationic. SDBS is an anionic surfactant. Compared to non-ionic surfactants, electrostatic repulsion makes the aggregation of monomers into micelles more difficult; thus, CMC is typically higher than non-ionic ones. Furthermore, the combination of anionic and non-ionic surfactants has shown promising synergistic effects in previous studies (Liu et al., 2021). This is because non-ionic surfactants, being uncharged, are highly compatible with both non-ionic and ionic surfactants. However, the CMC of mixed anionic/non-ionic surfactants cannot be estimated with the ideal solution theory because of the mentioned synergistic effect making the CMC smaller (Zhou et al., 2005).

Noteworthy, previous research investigated the effectiveness of SDBS and Tween 80 in removing petroleum hydrocarbons both alone (Lumia et al., 2020a) and as mixed surfactants (Zhou et al., 2005), with promising results. However, further research is necessary, considering the influence of operational conditions. Additionally, little is known about their effectiveness in dealing with contaminated sediment, whose properties can significantly differ from soils (Zhang and Zhu., 2010). Indeed, to the best of our knowledge, Tween 80 has only been studied for the remediation of petroleum hydrocarbon-contaminated sediments in Italy but as an enhancing agent in combination with other treatments (Chiou et al., 1998).

Along with surfactants, chemical oxidation has emerged as a particularly interesting remediation technique, due to its rapidity and effectiveness (Xu et al., 2022). Commonly used oxidizing agents include potassium permanganate, hydrogen peroxide, and ozone. In recent years, potassium ferrate (Fe(VI)) has emerged as a particularly effective oxidant, due to its oxidation potential, which is higher than that of commonly used oxidants (Kumar Rai et al., 2018).

The main advantage of Fe(VI) is the formation of non-toxic by-products after its reduction. In addition, during the Fe(VI) reduction process, iron intermediates (such as Fe<sup>5+</sup> and Fe<sup>4+</sup>) can accelerate oxidation reactions or act as useful precipitants (Fe<sup>3+</sup>) (Zhang et al., 2021). However, although the effectiveness of surfactant-assisted oxidation treatment has been demonstrated on a wide spectrum of pollutants, the applicability of this technique with the use of ferrate(VI) for the removal of TPHs has not been fully ascertained.

In this context, the experimental campaigns, carried out in synergy with the activities of Task 4.5.1, aimed to assess the feasibility of the combined use of oxidants and surfactants for the remediation of diesel-

contaminated soils and marine sediments. In particular, the oxidative efficiencies of potassium ferrate (an innovative oxidant) and potassium permanganate (a conventional oxidant) were compared. Moreover, the influence of the concentrations of the two oxidants and of the surfactant; sodium dodecylbenzene sulfonate (SDBS), in terms of effectiveness in the solubilization and oxidation of TPHs was evaluated. Finally, the effect of these compounds on the residual phytotoxicity of soil and sediments after treatment was studied.

#### ➤ MATERIALS AND METHODS (GENERAL INFORMATION)

For the experimental study of the effectiveness and potential of the SW, different experimental campaigns were proposed, with different batch test batteries.

Each campaign analyzed the sediments coming from the port of Augusta and/or Genoa: the contamination characteristics were generally similar to those defined in the previous paragraphs. In reality, depending on the study priorities, the sediments were used as is (TPH contamination, port of Genoa; Mercury contamination, port of Augusta), or altered with an overdose of synthetic contamination (single or mixed, mercury/TPH), in order to study the aspects related to hypothetical critical intervention scenarios.

The specificity of contamination and the operating conditions of the tests will be better specified in the respective paragraphs commenting on the results.

The experimental campaign was characterized by “sediment washing” tests on real marine sediments artificially contaminated by diesel fuel, using a simple Jar Test station (see [Figure 4.16](#)).



Figure 4.16 - Experimental station (Jar Test) used for washing tests

#### ➤ OPERATIONAL CONDITIONS, RESULTS AND MAIN CONCLUSION CONCERNING THE USE OF SURFACTANTS FOR SW

The sediments used during the experimental campaign were dredged from Augusta Bay (Italy), a contaminated site of national interest.

[Table 4.6](#) summarizes the main features of the real marine sediments. Nevertheless, they were further artificially contaminated with diesel fuel to achieve a higher level of total petroleum hydrocarbons (TPHs) contamination, compatible with the aim of the study. Specifically, diesel fuel was added to the raw sediment at a 1:10 volume-to-weight (v/w) ratio, corresponding to 100 mL of diesel per 1 kg of sediment. The contaminated sediment underwent daily manual mixing for 15 days, to enhance contaminant homogenization and promote the volatilization of the most volatile TPHs fractions. Subsequently, the drying phase was completed by placing the sample in an oven at 40°C for 72 hours, ensuring a uniformly contaminated sediment for the subsequent washing tests. The subsequent pretreatment phases focused on crushing and sieving the dried sediment, with the aim of isolating the fine fraction. This choice was driven by the fact that the concentration of hydrocarbons adsorbed onto the solid matrix usually is closely related to the specific surface area, becoming higher as the particle size decreases ([Rajabi et al., 2018](#)). Specifically, the dried sample was first crushed using a mortar and pestle to reduce particle size and then subjected to sieving. The sieving process was performed using a two-stage sieve system with mesh sizes of 2 mm and 63 µm. [Table 4.6](#) shows the characterization of the sediments used and the initial level of hydrocarbons before artificial contamination and pretreatment.

**Table 4.6** Main features of the sediments before contamination (Tiesi et al (2025)).

Analysis	Units.	Value
Residue at 105°C	%	53.5
pH	-	9
TOC	g/kg	2.2
Mercury	mg/kg <sub>DS</sub>	16
Hydrocarbons C<12	mg/kg <sub>DS</sub>	<0.3
Hydrocarbons C>12	mg/kg <sub>DS</sub>	130

After the artificial contamination, the sediment fraction < 63  $\mu\text{m}$  was characterized by a TPH concentration equal to 61108.65  $\text{mg kg}_{\text{DS}}^{-1}$  ( $\pm 8361 \text{ mg kg}_{\text{DS}}^{-1}$ ), in order to simulate a severe TPH pollution.

In the present study three different surfactants were tested: Tween 80 (a nonionic surfactant), SDBS (an anionic surfactant), and rhamnolipids (natural anionic biosurfactants), all three used individually and in combination to form mixed micelles. Each test was performed in duplicate to ensure more reliability of the results. The influence of surfactant concentration in the washing solution was assessed in terms of hydrocarbon removal efficiency from the sediments. After each test, the phytotoxicity of the treated sediment was evaluated by calculating the germination index (GI) using *Lepidium sativum* (garden cress) seeds. Specifically, the experimental campaign was divided into different tests. Preliminary washing tests were performed with tap water used as a blank control (test A). Subsequently, five series of tests were carried out at different surfactant concentrations: Test B involved the exclusive use of Tween 80; in Test C, washing was performed using SDBS alone; Test D investigated the combined use of SDBS and Tween 80 to generate mixed micelles; Test E assessed the effect of rhamnolipids alone, while Test F evaluated the synergistic use of Tween 80 and rhamnolipids. **Table 4.7** shows the different tests performed and the corresponding surfactant concentrations used for each tested condition.

**Table 4.7** Summary of the experimental tests carried out at different surfactants concentration (Tiesi et al (2025)).

Test	H <sub>2</sub> O	Tween80			SDBS			Rhamnolipids		
		0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
A	X									
B		X								
C					X		X			
D		X			X		X			
E								X		
F		X						X		
			X					X	X	

The surfactants used (Sodium Dodecyl Benzensulphonate – SDBS, Polyoxyethylene(20) sorbitan monooleate – Tween 80, and Rhamnolipids produced by *Pseudomonas aeruginosa*) were purchased from Sigma Aldrich. Surfactant solutions were prepared using distilled water.

The above surfactants were selected due to the different chemical composition (non-ionic, anionic and natural) and also because they were thoroughly applied in previous remediation applications (Paria, 2008; Lai et al., 2009; Bolan et al., 2023) but further research is needed, in particular for sediment washing. Furthermore,

these surfactants have different environmental behaviour. Indeed, SDBS is potentially toxic and persistent; Tween 80 is considered to be more environmentally friendly, due to its higher biodegradability (Zhang et al., 2024); despite this, among the three surfactants used, rhamnolipids are the most environmentally friendly because they do not accumulate in the environment, are non-toxic and are naturally produced by bacteria, making them a sustainable choice compared to synthetic surfactants (Ambaye et al., 2021). The different surfactants used have different CMCs: SDBS has a CMC of 212.57 mg L<sup>-1</sup>, Tween 80, a CMC of 13.1 mg L<sup>-1</sup>, instead, rhamnolipids from *Pseudomonas aeruginosa* have a CMC of 31 mg L<sup>-1</sup> (Lai et al., 2009; Di Trapani et al., 2023).

For all washing tests, an orbital shaker was used to promote contact between the solid matrix and the washing solution. Specifically, the samples composed of 10 g of sediment and 40 mL of solution, in a 1:4 ratio, were placed in Pyrex glass bottles, and using the orbital shaker, they were stirred at a speed of 100 rpm for 24 hours. All tests were performed in duplicate to ensure greater reliability of the results.

At the end of the tests, the samples were left to settle for 2 hours and after removing the supernatant, the solid component was left to air dry at room temperature.

The three different surfactants were used at variable concentrations in the washing solution (Table 2). For each surfactant used individually, the concentrations in weight tested were 0.2%, 0.4% and 0.6%. In the case of SDBS, concentrations were about 10, 20, and 30 times the CMC; for Tween 80, the concentrations were about 150, 300, and 450 times the CMC. For rhamnolipids, the concentrations were about 65, 130 and 195 times the CMC. When the washing solution was prepared using surfactants in synergy to promote the formation of mixed micelles (Tween 80 – SDBS and Tween 80 – Rhamnolipids), the concentrations in weight used were 0.2% - 0.2%, 0.2% - 0.4%, and 0.4% - 0.2%, respectively.

Concerning the **TPH removal efficiency with water and individual surfactants**, Figure 4.17 shows the TPH extraction efficiency achieved with water and the individual surfactants at different concentrations by weight in the washing solution. The results obtained from the washing tests showed that the TPH extraction rate improved when the surfactants were used in the washing solution compared to the washing test carried out with only water ( $\eta \approx 15\%$ ), also highlighting different behavior of the investigated surfactants. It is therefore evident that the presence of surfactants is strategic in enhancing the ability of TPH removal from sediment compared to water alone, for the reasons discussed below.

However, the mobilization efficiency achieved with water is consistent with previous studies on TPH-contaminated soils, where it was observed that washing with water alone led to the mobilization and subsequent removal of a non-negligible portion of TPH from the soil (Lai et al., 2009; Di Trapani et al., 2023).

Overall, as shown in Figure 4.17, the lowest efficiency in the case of individual surfactant was obtained using rhamnolipids at 0.2%, with TPH mobilization rate of  $\eta \approx 21\%$ . In contrast, the efficiency significantly increased with Tween 80 and SDBS at 0.2%, with mobilization rate of  $\eta \approx 44\%$  and  $\eta \approx 42\%$ , respectively.

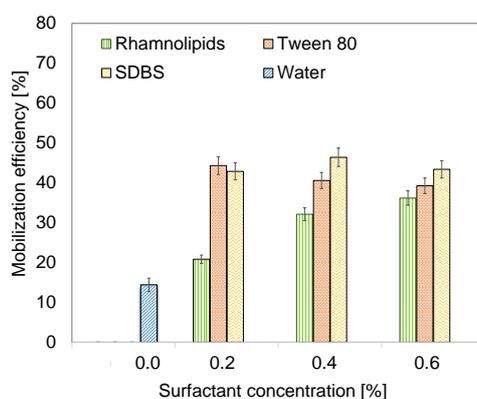


Figure 4.17 - TPH extraction yields from sediments using water and only surfactants individually at 0.2%, 0.4% and 0.6% (Tiesi et al., 2025).

The TPH extraction yield improvement obtained by using Tween 80, compared to washing with only water can be attributable to Tween 80's ability to solubilize and disperse hydrocarbons due to its amphiphilic structure, which allows effective interaction with hydrophobic hydrocarbon molecules (Kopanichuk et al., 2018). However, as shown in Figure 4.17, washing tests with 0.4% and 0.6% w/w Tween 80 solutions did not show a further increase in extraction yield; in fact, they were approximately 5% lower, suggesting that beyond a certain concentration, the surfactant's effectiveness slightly decreases, at least with marine sediment with such high TPH concentrations. It can be inferred that there is an optimal concentration threshold for surfactants like Tween 80, beyond which hydrocarbon removal performance tends to decline. The order of magnitude of the TPH removal rate is comparable to that of a recent study with similar contact time and Tween 80 at 100 CMC (Caetano et al., 2024). In particular, Caetano and co-workers monitored the contact time between TPH-contaminated soil and washing solution, from a few hours to three days, finding that the TPH-removal efficiency tended to stabilize to its best after 24-36 hours. However, in contrast with our findings, when the Tween 80's concentration was further increased up to 700 CMC, the TPH removal efficiency increased (above 80%). Nevertheless, it is worth noting that the physicochemical characteristics of the medium can significantly influence the washing performances (Saxena et al., 2023); in the study by Caetano and co-workers the authors used a soil fraction < 2 mm while in the present study a finer sediment fraction (< 0.063 mm) was used. Therefore, further studies are necessary, also to fully elucidate the relationship between marine sediment features and surfactant concentration and how these can influence the surfactant extraction performances.

Figure 4.17 also presents the TPH removal efficiencies obtained from washing tests with SDBS. It can be seen as the use of SDBS significantly increased the solubilization yields of hydrocarbons from the contaminated sediment. Overall, the yields obtained were slightly higher compared to those achieved with Tween 80 at the same concentration except for concentration at 0.2%. The maximum extraction rate was obtained with SDBS concentration of 0.4% w/w, reaching approximately 46%. Conversely, increasing the SDBS concentration to 0.6% w/w resulted in a moderate decrease in removal efficiency.

Although the efficiency of TPH removal generally increases when rising surfactant concentrations (Liu et al., 2021), some authors reported different findings that can be attributed to excessive micelle formation at high surfactant concentrations and that this circumstance may inhibit rather than enhance hydrocarbon solubilization. Indeed, similar behaviors were reported in previous experimental studies (Zhao et al., 2014), which highlighted that exceeding the CMC can sometimes reduce contaminant solubilization due to the excessive presence of micelles, potentially inhibiting solubilization capacity. Further studies (Urum and Pekdemir, 2004) found that in a treatment of soil washing with the surfactants lecithin, aescin, and tannin, as the surfactant concentration increased, the TPH removal efficiency decreased.

Furthermore, the results obtained with SDBS are consistent with previous research conducted by Di Trapani and co-workers on soil remediation through SDBS flushing (Di Trapani et al., 2023). Such study identified a threshold surfactants concentration value beyond which extraction performance declined. Specifically, TPH-contaminated soil was treated using the soil flushing technique at increasing SDBS concentrations (0.1%, 0.2%, 0.3%, 0.4% w/w). The highest removal yield was observed at an SDBS concentration of 0.2%. Although in the present study the maximum efficiency was achieved for SDBS concentration of 0.4%, TPH concentration can significantly influence the results (Lai et al., 2009; Saxena et al., 2023). Notably, the initial TPH concentration in the soil flushing study carried out by Di Trapani et al. (2023) was approximately one order of magnitude lower ( $\approx 6000 \text{ mg}_{\text{TPH}} \text{ kg}_{\text{DS}}^{-1}$ ) compared that of the present study.

It also appears that beyond the CMC, the concentration of surfactants played a predominant role rather than the number of times each surfactant exceeded its own CMC. Indeed, even if the CMC of SDBS was about one order of magnitude higher than that of Tween 80, at concentration of 0.2% the mobilization efficiency of the two surfactants was similar. Furthermore, at concentrations of 0.4% and 0.6%, SDBS removal efficiency was slightly above Tween 80 at the same concentration (Figure 4.17), despite the CMC of Tween 80 continued to be about an order of magnitude lower. In fact, anionic surfactants may be more effective than non-ionic surfactants due to the lower tendency to adsorption, as there can be a repulsion between the anionic surfactant and negatively charged soil particles (Li et al., 2019). Furthermore, recent studies suggested that Tween 80 shows worse performance related to the organic matter content of the treated soil (Chen et al., 2017). The results for Tween 80 and SDBS alone are in line with those of previous studies. In particular, Niu

and co-authors (Niu et al., 2020) found that SDBS at 1% had better performance ( $\eta > 50\%$ ) than Tween 80 ( $\eta < 40\%$ ) in removing TPH from highly contaminated soil. Additionally, Ritoré and colleagues (Ritoré et al., 2022) achieved better results with SDBS than with Tween 80 in TPH removal from soil (initial TPH concentration in soil above  $8,000 \text{ mg kg}^{-1}$ ). The authors tested soil with three different textures (silty clay, silt loam, and loamy sand), consistently obtaining better performance with SDBS; furthermore, the TPH removal rate always improved when moving from finer to coarser soils.

Notably, only one study was identified that investigated the washing of marine sediments contaminated with oil spills using SDBS. In that study, the authors (Shih et al., 2020) focused on PAHs and achieved a removal efficiency of 45% with SDBS at 100 times the CMC, i.e. close to our results. However, the PAH concentration in the untreated sediment was approximately three orders of magnitude lower than that of the present study.

Concerning sediment washing with rhamnolipids alone, as shown in Figure 2, the TPH removal yield always increased with rising surfactant concentrations. Accordingly, TPH-efficiency removal rate of 21% was achieved with rhamnolipids at 0.2%; a substantial removal increase ( $\eta \approx 32\%$ ) was achieved with rhamnolipids at 0.4%. Finally, the highest removal rate ( $\eta \approx 36\%$ ) was achieved with rhamnolipids at 0.6%.

A similar trend was observed in the experiment carried out by Lai and co-workers (Lai et al., 2009) where Rhamnolipids from *Pseudomonas aeruginosa* were used at different concentrations (from 0.05% to 0.2% w/w) in TPH-contaminated soil and the highest removal rate was achieved with rhamnolipids at 0.2%.

However, the removal efficiency of rhamnolipids was consistently lower than that of SDBS and Tween 80; this result contrasted with what highlighted in previous studies where Tween 80 was found to be less effective than rhamnolipids (Liu et al., 2021). However, the mentioned studies focused on soil rather than sediment. Thus, the lower performance of rhamnolipids might be attributed to sediment properties, which differ from soils, as well as grain size and TPH concentration, which can influence the results (Lai et al., 2009; Saxena et al., 2023).

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On the other hand, concerning the **TPH removal efficiency with mixed surfactants**, Figure 4.18 summarizes the TPH mobilization efficiency with mixed SDBS-Tween 80 (Figure 4.18a) and Rhamnolipids-Tween 80 (Figure 4.18b), respectively.

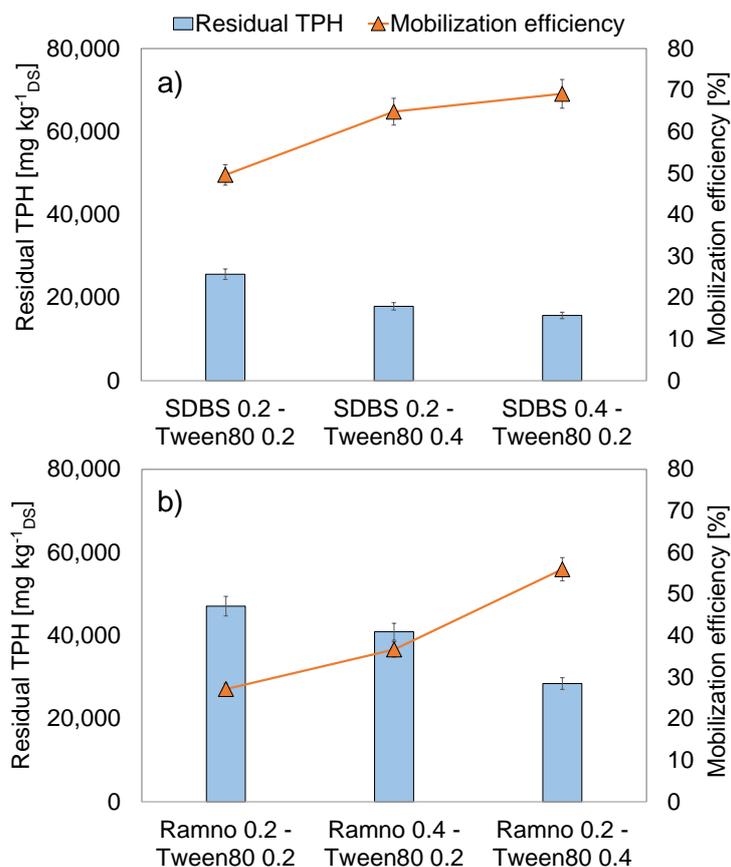


Figure 4.18 - TPH extraction yields from sediments using SDBS and Tween 80 (a) and rhamnolipids and Tween 80 (b) as mixed surfactants ( )

From the observation of data reported in Figure 4.18, it is worth noting that the removal efficiency of TPH from sediment led to substantial increase in the removal yield of TPH in the case of SDBS and Tween 80 as mixed micelles (Figure 4.18a). In particular, the best results ( $\eta \approx 69\%$ ) were achieved with SDBS at 0.4% and Tween 80 at 0.2%. Similarly, SDBS at 0.2% and Tween 80 at 0.4% reached a removal yield of about 65%.

Finally, SDBS and Tween 80 both at 0.2% led to a removal yield of about 50%, slightly higher compared with the results achieved for each individual surfactant at a concentration of 0.4% (Figure 4.17).

It is important to note that the other combination of mixed surfactants (i.e., Tween 80 and Rhamnolipids) started with a lower removal efficiency, even below that of Tween 80 or SDBS alone. Interestingly, as shown in Figure 4.18b, Rhamnolipids at 0.2% and Tween 80 at 0.4% led to a significant increase of the TPH removal yield, allowing to reach the third best result of all ( $\eta \approx 56\%$ ). Furthermore, when using rhamnolipids at 0.4% and Tween 80 at 0.2%, a removal efficiency of 37% was achieved, i.e. above all the experiments with rhamnolipids alone.

Additionally, the increase in rhamnolipids concentration confirmed the parallel increase of TPH-removal efficiency noted by other authors when using rhamnolipids alone (Lai et al., 2009). Thus, further studies should investigate the increase that could be achieved in TPH removal yields when using Tween 80 at concentration of 0.2% or 0.4%, while increasing rhamnolipids concentration even above 0.4%.

Overall, our results confirmed that the use of anionic and non-ionic surfactants to form mixed micelles has great potential, offering the best results, in terms of mobilization efficiency. Indeed, as anticipated, previous studies have demonstrated that the combination of anionic and non-ionic surfactants exhibits synergistic effects. Mixed anionic and non-ionic micelles are formed through ion-dipole interactions between distinct hydrophilic groups, which mitigate electrostatic and spatial repulsion among surfactants of the same type. This mixture is characterized by a lower CMC, reduced adsorption and precipitation losses, and enhanced

resistance to variations in temperature, inorganic salts, pH, and other environmental conditions (Liu et al., 2021). Our results are line with the study of Wu and colleagues (Wu et al., 2024) where mixed micelles were used to remove benzo(a)pyrene from soil. In particular, the authors used an anionic surfactant (MES) and a non-ionic surfactant (APG), both environmental-friendly and biodegradable, achieving promising results thanks to the synergistic effects. Given the paucity of studies in the scientific literature on the use of different surfactants to form mixed micelles for soil and sediment washing in TPH-contaminated areas, the results obtained in this study represent a significant advancement. These findings highlight the need for further investigation to optimize surfactant selection in mixed micelles formation and enhance remediation efficiency.

Finally, in order to evaluate the effects on the potential reuse of the treated sediments, the residual eco-drought was evaluated by means of eco-toxicity tests.

Particularly, the phytotoxicity of sediment samples (both raw and after washing treatments) was determined using the germination index (GI) by testing *Lepidium sativum* (garden cress) seeds according to APAT (2004b). Ten seeds were placed on a paper filter inside Petri dishes. A negative control was prepared, consisting of a matrix which does not contain substances that could inhibit germination and root elongation, while for each washing test carried out three dilutions of the sample with uncontaminated soil (25%, 50% and 100%) corresponding to a total amount of 10 g of dry mass for each test. Additionally, GI was also evaluated on contaminated and untreated sediment samples (positive control). Petri dishes were placed in an incubator at  $25 \pm 2^\circ\text{C}$  for 72 h. At the end of the incubation period, the number of germinated seeds was assessed and the root length was measured. The germination index (GI) was calculated by multiplying the number of germinated seeds (G) and the root length (L). The germination index (GI) results were used to calculate the effect, expressed as a percentage (GI%), compared to the control using the following equation, where S and C represent the samples and negative control, respectively.

$$GI = \frac{G_s \cdot L_s}{G_c \cdot L_c} \cdot 100 [\%]$$

From the results obtained in the phytotoxicity tests by germination index, it has emerged that the use of surfactants had different effects on the phytotoxicity characteristics of the soil after washing treatments. Figure 4.19 reports the GI data obtained for all the tests carried out, evaluated as average values. The high concentrations of hydrocarbons in the contaminated sediment had a highly negative impact on the phytotoxicity of the sediment. In the untreated contaminated sediment sample, the germination of *Lepidium sativum* seeds was almost zero with a very low GI value (2.24%) compared to the negative control. However, the results obtained show a different role played by the surfactants used for washing. In fact, the GI values obtained after treatment with Tween 80 (3.7%) were significantly higher than those obtained from the samples treated with SDBS (0.54%) whose high phytotoxicity was already known in literature (De Marines et al., 2025). This behavior was also observed in the Tween 80/SDBS mixtures (6.07%). This result further highlights the opportunity to use mixed solutions of Tween 80/SDBS in sediment washing treatments, not only to improve the hydrocarbon removal efficiency, but also to reduce residual phytotoxicity. This effect could be attributed to the presence of bioavailable organic carbon in Tween 80, which appears to increase root permeability, thereby facilitating nutrient uptake from the soil (Cheng et al., 2017). The use of rhamnolipids showed a significant improvement in the germination index (22.8%) compared to raw sediment, highlighting the ability of these biosurfactants to reduce the impact of contaminants present in the soil. This positive effect is attributable to the surfactant properties of rhamnolipids, which promote biodegradation and mobilization of toxic compounds. When rhamnolipids are combined with Tween 80, a further improvement in the germination index was observed (41.5%) compared to the use of rhamnolipids alone. This suggests a synergistic effect between the two surfactants, probably due to the ability of Tween 80 to improve the solubility of contaminants, reducing their toxicity and facilitating plant recovery.

The fact that the toxicity of SDBS resulted as the highest among the three surfactants investigated in our study was already known (Liu et al., 2021). Indeed, although it is often used as detergent and discharged with greywater, some studies focused on its removal from greywater because the excessive use can be detrimental to human health and the environment. It can induce blistering and toxicity in aquatic systems, affecting the quality of water. Additionally, due to its low biodegradability, SDBS may persist in the environment for extended periods (Feng et al., 2022). Thus, although its use alone or in combination with Tween 80 led to the best TPH-removal rate, its use can be partially in contrast with the scope of sediment remediation and green technologies because of the risk of secondary contamination (Wu et al., 2024). Conversely, rhamnolipids represent an example of biosurfactants that are gaining interest due to their environmentally friendly characteristics and lower toxicity compared to synthetic surfactants such as SDBS and Tween 80 (Ambaye et al., 2021; Liu et al., 2021).

Notably, this approach is in line with the proposal for a Directive by the European Parliament on soil monitoring and resilience (European Commission, 2023) which emphasizes the importance of remediating contaminated soils using methods that do not harm the soil ecosystem. Indeed, the directive stresses that remediation treatments should not cause secondary pollution or make the soil ecotoxic.

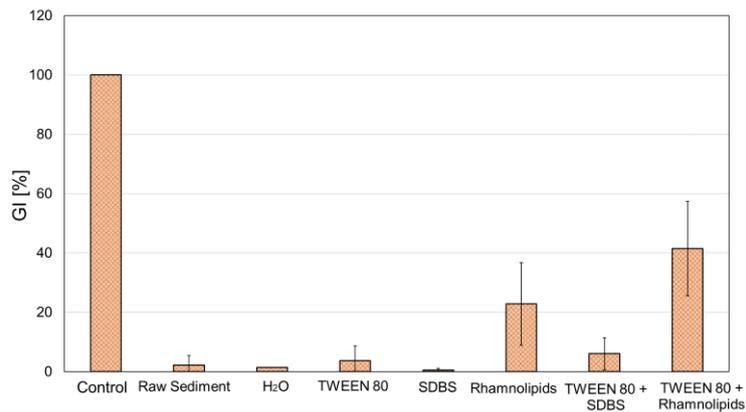


Figure 4.19 - Average values of the germination index for the different samples (Tiesi et al. 2025)

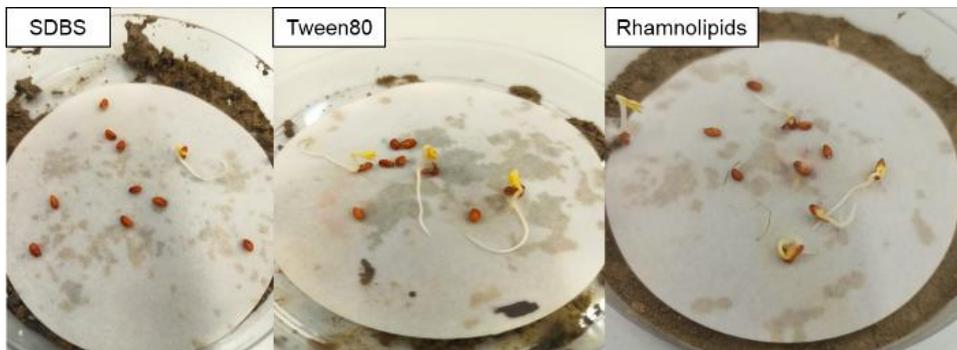


Figure 4.20 - Petri dishes with germinated and non-germinated seeds after 72 hours of incubation, in the case of contaminated sediments treated with SDBS, Tween 80, and rhamnolipids

Table 4.8 reports the average number of germinated seeds and the average length of sprouts obtained for all tests performed.

**Table 4.8** Number average of germinated seeds and length average of sprouts (in brackets the standard deviation) (Tiesi et al., 2025).

Sample	Number of germinated seeds	Length of sprouts [mm]
Control	6 ( $\pm 3.2$ )	5.04 ( $\pm 3.12$ )
Raw Sediment	0.33 ( $\pm 0.8$ )	0.66 ( $\pm 0$ )
H <sub>2</sub> O	0.33 ( $\pm 0.6$ )	0.42 ( $\pm 0$ )
Tween 80	0.67 ( $\pm 1$ )	3.17 ( $\pm 4.43$ )
SDBS	0.33 ( $\pm 0.7$ )	0.43 ( $\pm 0.19$ )
Rhamnolipids	2.33 ( $\pm 3$ )	1.20 ( $\pm 1.03$ )
Tween 80 + SDBS	0.33 ( $\pm 0.5$ )	1.69 ( $\pm 1.5$ )
Tween 80 + Rhamnolipids	4 ( $\pm 3.4$ )	1.69 ( $\pm 1.13$ )

#### ➤ OPERATIONAL CONDITIONS, RESULTS AND MAIN CONCLUSION CONCERNING THE USE OF FERRATE FOR SW

The aim of the study (**Not yet published**) was to evaluate the feasibility of the combined use of oxidants and surfactants for the remediation of marine soils and sediments contaminated by diesel fuel. In particular, potassium ferrate(VI) and potassium permanganate were compared in terms of oxidation efficiencies. The tests were conducted in slurry mode (100 g of soil/sediment and 500 mL of solution) by means of Jar Test. The results obtained from the oxidation tests with Fe(VI) carried out on the soil showed TPH removal efficiencies higher than 90%. Also in the tests carried out with permanganate the results showed high removal efficiencies, although lower than those obtained from the tests conducted on the soil. These different results can be attributed to the content of natural organic matter (NOM) in the soil, whose presence improves the oxidation efficiency of ferrate (VI), worsening, instead, that of permanganate. With reference to marine sediments, whose tests are still ongoing, it is likely to expect different results, since they are characterized by a TOC significantly lower than that of the soil.

In fact, although the effectiveness of the surfactant-assisted oxidation treatment on a broad spectrum of pollutants has been demonstrated, the applicability of this technique with the use of ferrate(VI) for the removal of TPHs has not been fully ascertained (Kumar Rai et al., 2018; Zhang et al., 2021).

The experimental campaign was divided into two periods.

In the first period, tests were carried out on soil (Task 4.5.1 of RETURN PROJECT) and in the second period on marine sediments (Task 4.5.1 and 4.5.3 of RETURN PROJECT).

The tests were conducted in slurry mode (100 g of soil/sediment and 500 mL of solution) by means of Jar Test. The procedure involved a rapid mixing at 200 rpm for 5 minutes, followed by a slow mixing at 40 rpm for 48 hours and finally a sedimentation phase of 45 minutes, in order to separate, by gravity, the liquid phase from the solid phase. The liquid and solid samples (the latter after drying in the air for 3 days) obtained were subsequently subjected to the TPH extraction procedure. In all tests, SDBS was dosed at the beginning of the test, in order to favor the solubilization of TPH; the oxidant, instead, was dosed after 24 hours, to facilitate the oxidation of the hydrocarbons passed into solution.

For each test, the following were analyzed: (i) the influence of the concentration of surfactant (0.1%, 0.2% and 0.4% by weight) and oxidant (0.5%, 1% and 1.5% by weight) in terms of the effectiveness of solubilization and oxidation of TPH and (ii) the germination index (IG%), to evaluate the residual phytotoxicity of soil and sediments. Furthermore, tests were performed with water only, which represented the blank control. Three replicates were performed for each condition.

Soil and sediment samples were artificially contaminated with a quantity of diesel fuel equal to 1% by weight, in order to reach an initial TPH concentration of approximately 5000 mg/kgSS. Before starting the tests, the samples were mixed manually for 15 days in order to allow the volatilization of the most volatile components. As for the sediments, at the end of the mixing days, these were first dried at 40°C for 72 hours and finally ground and sieved twice, with 2 mm and 63 µm meshes. The main characteristics of the soil and sediments are reported in **Table 4.9**.

**Table 4.9** Characterization of soil and sediment in the test of ferrate (De Marines et al., 2025).

	Soil	Sediment
Clay [%]	15	-
Silt [%]	22	-
Sand [%]	63	-
pH	7.8	9
TOC [g Kg <sup>-1</sup> ]	31.4	2.2
TPH [mg Kg <sup>-1</sup> ]	4670	4754

The results obtained from the control blank showed a modest removal of TPH from both soil (~30%) and marine sediments (~25%). Instead, in the samples treated with Fe(VI)/KMnO<sub>4</sub> and SDBS the results highlighted an increase in the TPH removal efficiency with increasing oxidant dose.

In particular, **Figure 4.21** shows the results obtained from the oxidation tests carried out on the soil. In general, the highest yields were obtained in the tests conducted with Fe(VI). In fact, it was observed that the dosage of ferrate alone (**Figure 4.21a**) guaranteed a high removal efficiency of TPH from the solid phase, which increased with the increase in its concentration, allowing values between 90% and 95% to be reached. The presence of the surfactant, on the other hand, did not appear to have significantly influenced the treatment yield; in fact, in the samples in which SDBS was present in solution, the maximum removal efficiency obtained was equal to 96%. With reference to the liquid phase, the residual concentrations of TPH, in all the tests carried out, were always lower than 7 mg/L.

The high yields obtained are likely attributed to the fact that Fe(VI), in addition to oxidizing the TPH in solution, also oxidized the hydrocarbons remaining adsorbed on the soil. The high effectiveness of ferrate against the latter is likely attributable to the NOM content in the soil. Several studies reported in the literature (**Barişçi, 2017; Deng et al., 2018; De Marines et al., 2024**) have demonstrated, in fact, that the presence of NOM, and in particular of humic acids, leads to the activation of ferrate and its reduction to Fe(V) and Fe(IV), molecules with a reactivity up to 2-5 orders of magnitude higher than Fe(VI).

The removal yields obtained from the tests carried out with permanganate, however, were significantly lower (**Figure 4.21b**) and ranged between 65% and 67%. In addition, in this case, the SDBS did not seem to have significantly influenced the treatment yields, allowing the removal of TPH to increase up to approximately 69%. Furthermore, similarly to what was found in the tests with ferrate, the concentrations of TPH in the liquid phase were negligible in all the tests and less than 5 mg/L. The different results obtained are due, again, to the NOM content. The study conducted by **Ritoré et al. (2023)** has in fact highlighted the influence of NOM on the oxidation rate of permanganate. In particular, it emerged that an increase in the NOM content leads to a decrease in oxidation by KMnO<sub>4</sub>. Considering this, soil organic matter (TOC = 31.4 g/kg) increased the oxidative efficiency of Fe(VI) and, conversely, reduced that of permanganate.

On the other hand, the oxidation tests on marine sediments are still being carried out and the data processing is not sufficient to support the discussion. Nevertheless, the preliminary results appear significantly different for the two types of sediments coming from the ports of Genoa and Augusta. The results are probably linked to the different organic content (NOM) and the history of contamination of the sediments which, being significantly different, could favor the oxidation yields with permanganate rather than those with ferrate or vice versa.

In any case, the study conducted so far has confirmed the effectiveness of the treatment with ferrate, also highlighting the almost negligible role of the surfactant. The tests carried out have shown how the effectiveness of the process is strongly influenced by the organic matter present in the solid matrix, in particular by humic acids. These, in fact, present in greater quantities in the soil, have contributed to the activation of the ferrate, improving its oxidative performance.

At the same time, NOM has reduced the efficiency of the permanganate.

With reference to marine sediments, the results will be available soon and will allow a broader comparison of the behavior of the oxidants and surfactant used. The results of the phytotoxicity test have shown low values of Germination Index both in the soil and in the sediments, indicating an inhibitory effect on the growth of *Lepidium sativum*.

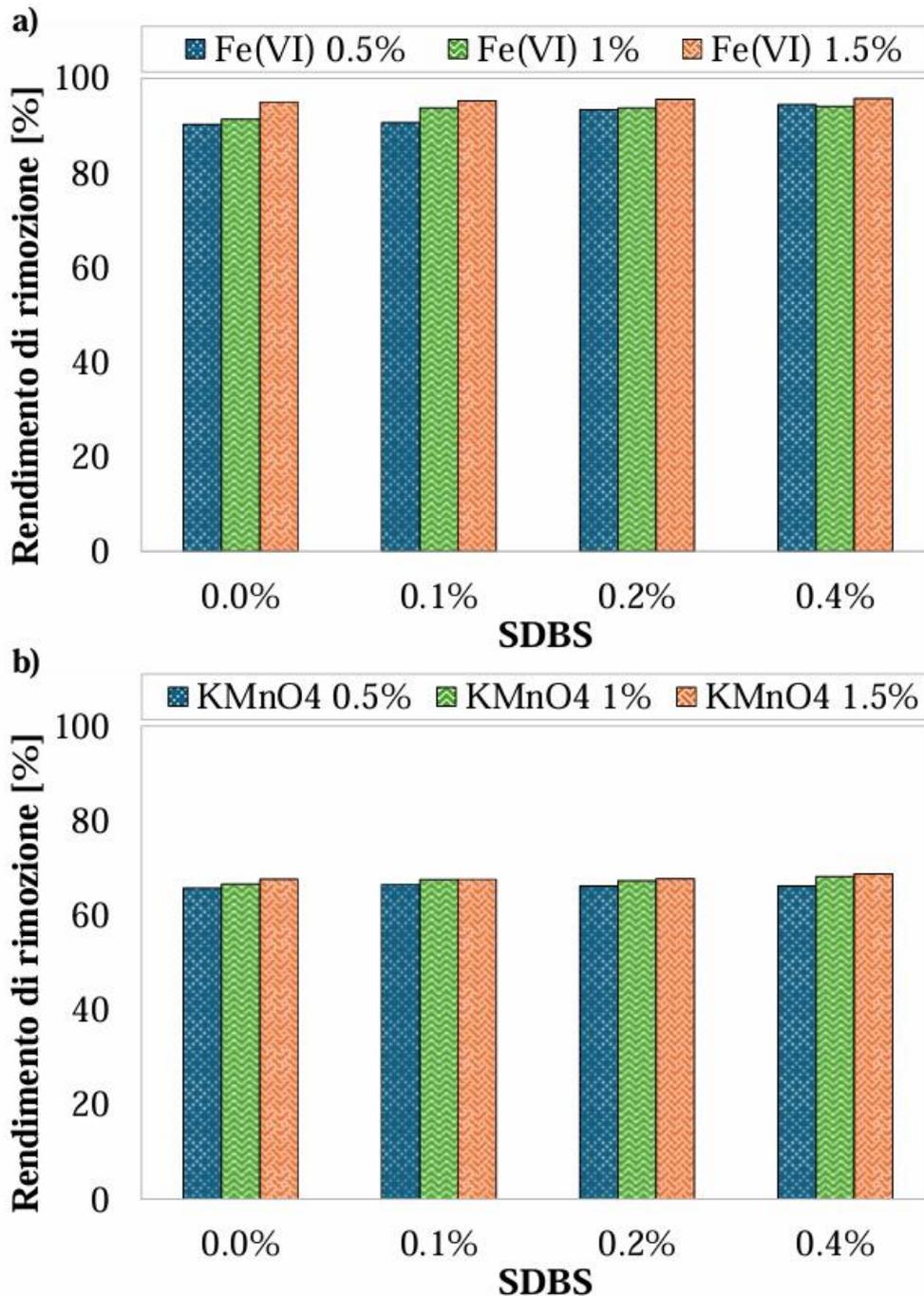


Figure 4.21 - Removal yields of TPH from soil after treatment with Fe(VI) and SDBS (a) and after treatment with KMnO4 and SDBS (b) (DE Marines et al., 2025)

## SWOT AND FMEA OUTPUT

The RETURN project, in general, also includes the multi-risk analysis approach regarding processes and procedures aimed at mitigating impacts (environmental, climatic, etc.).

In the context of the study of **Task 5.4.3** (marine sediment remediation), this aspect is very complex and closely linked to the historical "Know How" and to the different human-biota-environment interactions. For this reason, achieving a complete and exhaustive risk analysis is challenging, also because the process itself requires continuous and constant adaptation.

On the other hand, the numerous aspects to be considered, technical or site-specific, as recalled in the previous paragraphs, make the process even more complicated and requires significant interdisciplinary efforts.

In order to achieve the project objectives, and at the same time propose formats or tools useful for future development, the task has planned to deepen the "Proof of Concept" (POC) of the port of Genoa which is a commercial/urban port, technically more conventional than industrial ports clearly contaminated (and which fall within SI sites such as that of Augusta).

In this context, the Deliverable proposes two semi-qualitative risk analysis approaches, the SWOT and the FMEA previously mentioned, applied to the POC in a complete (SWOT) or proactive way on an "example node" FMEA

### SWOT ANALYSIS

Sediment management and remediation are critical environmental tasks, often involving complex decisions due to the interplay of ecological, economic, social, and technical factors. As discussed above, applying a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis provides a structured and comprehensive framework for evaluating these initiatives, leading to more effective and sustainable outcomes.

SWOT analysis proves invaluable throughout sediment management and remediation projects, from initial assessment and planning to implementation and post-remediation monitoring. Here is a disquisition on its application:

#### 1. Strengths (Internal Positive Factors)

Identifying internal strengths helps advantage existing capabilities and resources for optimal project execution. For sediment management and remediation, these might include:

- **Established Expertise and Technology:** Availability of skilled personnel, specialized equipment (dredges, dewatering technologies, treatment facilities), and proven remediation techniques (e.g., capping, *in situ* treatment, bioremediation).
- **Robust Regulatory Frameworks:** Clearly defined environmental regulations, permitting processes, and quality standards for sediment disposal and treatment, which provide legal impetus and guidance.
- **Existing Infrastructure:** Proximity to laboratories for sediment analysis, waste disposal sites, or beneficial reuse facilities (e.g., for dredged material).
- **Strong Stakeholder Collaboration:** Pre-existing positive relationships with regulatory bodies, local communities, industry partners, and academic institutions, fostering cooperation and smoother project implementation.
- **Financial Resources:** Dedicated funding or budget allocations for sediment management programs, ensuring the feasibility of projects.
- **Comprehensive Baseline Data:** Availability of extensive historical data on sediment contamination levels, hydrodynamic conditions, and ecological characteristics, which informs remediation strategies.

## 2. Weaknesses (Internal Negative Factors)

Recognizing internal weaknesses allows for proactive mitigation strategies and resource allocation to overcome limitations. Common weaknesses in sediment management and remediation include:

- **Limited Funding and Resources:** Insufficient budget, lack of specialized equipment, or shortage of trained personnel, potentially hindering the scope or effectiveness of remediation efforts.
- **Technological Gaps:** Absence of cutting-edge remediation technologies suitable for specific contaminant types or site conditions, or a lack of experience in applying novel approaches.
- **Bureaucratic Inefficiencies:** Cumbersome permitting processes, inter-agency coordination challenges, or slow decision-making, which can delay projects.
- **Lack of Public Awareness/Support:** Limited understanding or opposition from local communities regarding the necessity or methods of sediment remediation, leading to social friction.
- **Data Deficiencies:** Insufficient or outdated baseline data on sediment contamination, leading to uncertainties in risk assessment and remediation design.
- **Operational Constraints:** Logistical challenges due to site access, weather conditions, or the presence of submerged infrastructure, influencing remediation operations.
- **Legacy Contamination Issues:** The presence of complex mixtures of contaminants, including recalcitrant organic pollutants or heavy metals, making remediation more challenging.

## 3. Opportunities (External Positive Factors)

Identifying external opportunities enables organizations to capitalize on favorable conditions and trends, enhancing project success and sustainability. These may include:

- **Technological Advancements:** Emergence of innovative and more cost-effective remediation technologies (e.g., nanotechnology, advanced oxidation processes, gene editing for bioremediation) that can improve efficiency and reduce environmental impact.
- **Government Grants and Incentives:** Availability of funding programs, tax breaks, or subsidies for environmental protection, particularly for large-scale remediation projects.
- **Public and Political Will:** Growing public awareness and political emphasis on environmental protection, leading to increased support and resources for sediment remediation.
- **Beneficial Reuse Potential:** Opportunities to valorize dredged material for construction, land reclamation, habitat creation, or agricultural purposes, reducing disposal costs and promoting circular economy principles.
- **International Collaboration:** Partnerships with international organizations, research institutions, or other countries facing similar sediment contamination issues, allowing for knowledge sharing and joint projects.
- **Ecosystem Restoration Synergies:** Integration of sediment remediation with broader ecosystem restoration initiatives (e.g., wetland creation, fisheries enhancement), maximizing environmental benefits.
- **Market for Remediation Services:** A growing demand for specialized environmental consulting and remediation services, creating business opportunities.

## 4. Threats (External Negative Factors)

Anticipating external threats allows for the development of contingency plans and risk mitigation strategies to minimize potential adverse impacts. Potential threats include:

- **Economic Downturns:** Budget cuts or reduced funding for environmental projects during economic recessions, jeopardizing ongoing or planned remediation efforts.
- **Regulatory Changes:** Unfavorable changes in environmental laws or standards that could increase project costs, introduce new liabilities, or make certain remediation methods unfeasible.
- **Natural Disasters:** Extreme weather events (floods, storms, droughts) that can remobilize contaminated sediments, damage remediation infrastructure, or complicate operations.
- **Public Opposition/Litigation:** Organized opposition from local communities, environmental groups, or legal challenges that can delay or halt projects.

- **New Contaminants:** Emergence of previously unknown or unregulated contaminants (e.g., microplastics, PFAS) that require new assessment and treatment approaches.
- **Supply Chain Disruptions:** Unavailability of critical materials, equipment, or specialized services required for remediation due to global events or logistical issues.
- **Climate Change Impacts:** Rising sea levels, altered precipitation patterns, and increased storm intensity, which can exacerbate sediment contamination issues or complicate remediation efforts.
- **Competitive Landscape:** Intense competition among remediation companies for contracts, potentially driving down prices and affecting project quality.

The systematic SWOT proposed for POC of RETURN, analysis provides a powerful lens through which to examine sediment management and remediation projects. By thoroughly assessing internal strengths and weaknesses, and external opportunities and threats, stakeholders can develop more robust, resilient, and effective strategies. This structured approach facilitates informed decision-making, optimizes resource allocation, mitigates risks, and ultimately contributes to the successful and sustainable restoration of contaminated aquatic environments. It encourages a holistic view, moving beyond purely technical considerations to integrate economic, social, and environmental dimensions into the planning and execution of these vital environmental endeavors.

The tables of the analysis available in the worksheet attached to this DVL 4.5.5 are reported below

➤ Team

																							
TASK 5,3: Multi-risk approaches for the treatment of marine sediments in the port of Genoa																							
<b>SWOT team</b>																							
<b>S</b>	Strengths																						
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Redatto	Ruolo	Aspetti scientifici Task																					
<i>Prof. Ing. Gaetano Di Bella</i>	Responsabile UKE	Task Leader																					
<i>Prof. Ing Daniele Di Trapani</i>	Responsabile UNIPA	Component																					
<i>Prof. Marco Capello</i>	Responsabile UNIGE	Component																					
<b>Final Draft</b>		10/07/2025																					

Figure 4.22 - SWOT team

➤ Description of the method

	<p>TASK 5,3: Multi-risk approaches for the treatment of marine sediments in the port of Genoa</p>
<h2 style="background-color: #d9e1f2; padding: 5px;">Description of the method</h2>	
<p>The definition of risk and Risk-based thinking have entered in a preponderant way in quality systems with the latest version of the ISO 9001 standard. These concepts are in fact made explicit in the standard, but were already present "between the lines" even in the 2008 version.</p> <p>The ISO 31000 standard defines risk as an effect of uncertainty on objectives. It is easy to deduce from this definition how this can generate both a positive event and a negative event, although in everyday meaning we are used to associating risk with a purely negative event.</p> <p>Risk analysis consists first of all in the identification of the risk and its nature, but also in the analysis of the causes and potential consequences. Only by understanding these factors will it be possible to make choices to adequately address them.</p> <p>A tool to support organizations is certainly the SWOT analysis.</p> <p>Also known as the SWOT matrix, this tool allows you to analyze positive and negative aspects of the internal and external context. SWOT is an acronym of some words in English, which translated into Italian correspond to Strengths, Weaknesses, Opportunities and Threats. The first two are aspects related to the internal context and are specific to the organization. The last two instead are related to the external context, all those factors that do not concern the organization but everything that revolves around it.</p> <p><b>Strengths (S)</b> – These are the aspects considered strong of the organization, in which it excels</p> <p><b>Weaknesses (W)</b> – Unlike the previous ones, these are the points in which the organization is more lacking or at least not sufficiently prepared</p> <p><b>Opportunities (O)</b> – These are the opportunities that arise from everything that surrounds the organization. Geographical location, the presence of actors in the territory, legislative decrees, etc. can be useful for this purpose.</p> <p><b>External Threats (T)</b> – The same factors that can represent opportunities, for organizations that are not adequately prepared automatically become threats.</p> <p>The SWOT analysis should help understand the factors surrounding the organization to place them in the right position. The next effort that will then have to be made will be to try to transform the weaknesses into strengths and the threats into opportunities.</p> <p>We can easily see how even the risks can (and must) be placed within the matrix, divided into internal context and external context. In this phase, identifying and evaluating the risks is an almost obligatory step to make the SWOT analysis effective. Transforming the risks into opportunities to be seized or into strengths thus becomes the new corporate mission, which fully marries the new version of ISO 9001.</p> <p>A considerable effort for organizations, but which can lead to unimaginable results.</p>	

Figure 4.23 - SWOT Description method

➤ Strength's selection

Table 4.10 Step 1 - Strength's selection

<b>STEP 1 - Select possible Strengths to include in the SWOT</b>		
<i>The analysis will be done for all SWOT factors</i>		
<i>You can add additional factors below the list</i>		
<i>Select Yes or No to include the field in the Strengths - No limit on the number of selections</i>		
Check list	Include in SWOT (Si=Yes/No)	If Included in SWOT Report an Action
<i>Deepening of port seabed to improve infrastructure efficiency</i>	Si	<i>Preparatory work for the correct development of port activities</i>
<i>Resilienza dei sistemi naturali, specialmente in ambienti fortemente antropizzati</i>	Si	<i>Complex aquatic systems have their own bio-geo-chemical equilibria</i>
<i>In-depth knowledge of the physical-chemical, ecotoxicological and microbiological characteristics of sediments</i>	Si	<i>Complete characterization in accordance with current legislation</i>
<i>Knowledge of the chemical and ecotoxicological characteristics of the pollutants present</i>	Si	<i>Complete characterization in accordance with current legislation and verification of exceeding contamination thresholds</i>
<i>Complete knowledge of the spatial distribution of potential biotic and abiotic targets of the emerged and submerged compartment</i>	Si	<i>Mapping of biocenoses and mapping of environmental protection areas (SIC/ZPS)</i>
<i>Appropriate size of dredge material management areas</i>	Si	<i>Large areas potentially exploitable for direct or accessory processes</i>
<i>Extensive experience in managing dredging operations and port maintenance</i>	Si	<i>Multi-year management of port infrastructures with different logistical needs</i>
<i>Previous experience of research groups in the remediation of contaminated marine sediments</i>	Si	<i>Consolidated experience of research groups on the topic, to be used as a starting point for new and integrated research</i>
<i>Using real contaminated marine sediments</i>	No	
<i>In-Situ Bioremediation treatments</i>	No	
	No	
	No	
	No	

➤ Weaknesses' selection

Table 4.11 Step 2 – Weaknesses' selection

<b>STEP 2 - Select possible weaknesses to include in the SWOT</b>		
<p><i>The analysis will be done for all SWOT factors</i></p> <p><i>You can add additional factors below the list</i></p> <p><i>Select Yes or No whether to include the field in Weaknesses - No limit on the number of selections</i></p>		
Check list	Include in SWOT (Si=Yes/No)	If Included in SWOT Report an Action
<i>Lack of producers or operators of sediment treatment plants</i>	Si	<i>Encourage local entrepreneurship to invest in remediation treatments</i>
<i>Presence of particular biocenoses in the surroundings of the dredging areas</i>	Si	<i>Implementation of a Site Specific Environmental Monitoring Plan</i>
<i>Limitations in management options</i>	Si	<i>Applications of multi-criteria decision making processes evaluating technical and economic aspects Implementation of a Site Specific Environmental Monitoring Plan</i>
<i>Lack of hazardous waste landfills near dredging sites</i>	No	
<i>Complexity of managing environmental processes</i>	Si	<i>Strengthen Know-How by crossing different professional figures and project experiences</i>
<i>Validity times of limited characterizations</i>	No	
<i>Heavy maritime traffic near dredging areas</i>	No	
<i>Complex sediment management procedures</i>	Si	<i>Foresee in the design phase all possible scenarios and critical issues during the management of dredging works</i>
<i>Complex and difficult to control type of processing</i>	Si	<i>Use of proven dredging technologies that limit resuspension of material throughout the water column</i>
<i>Numerous bureaucratic and institutional steps</i>	No	
<i>Restriction of vessel traffic during dredging operations</i>	Si	<i>Optimization of the dredging process by favoring techniques with significant flow rates</i>
<i>Difficulty in finding multiple real contaminated marine sediments in a short time</i>	No	
<i>High costs for remediation techniques based on thermal and chemical/physical processes Difficulty in finding multiple real contaminated marine sediments in a short time</i>	Si	<i>Applications of eco-friendly and cost-effective strategies such as degradation of contaminants by microbial populations</i>
<i>High costs and high environmental impact for the disposal of contaminated sediments in landfills</i>	Si	<i>Search for alternative solutions to landfill disposal</i>
<i>Bioremediation treatments</i>	Si	<i>Risk of long treatment times. To optimize them, we will try to apply combined treatments (treatment train)</i>
	No	

➤ Opportunities' selection

Table 4.12 Step 3 – Opportunities' selection

<b>STEP 3 - Select the possible Opportunities to include in the SWOT</b>		
<i>The analysis will be done for all SWOT factors</i>		
<i>Puoi aggiungere ulteriori fattori in basso alla lista</i>		
<i>Select with Yes or No whether to include the field among the Opportunities - No limit on the number of selections</i>		
Check list	Include in SWOT (Si=Yes/No)	If Included in SWOT Report an Action
Greater draft of the port seabed	Si	Opportunity to increase naval traffic with an impact on the economic and social fabric of the territory
Valorisation of the sediment resource	No	
Job opportunities and creation of related industries	Si	Creation of a new construction site providing job opportunities with repercussions on the economic and social sector of the area
Securing and remediating contaminated seabeds	Si	Removal of those contaminated sediments that are potential sources of secondary contamination
Study of new remediation techniques through a holistic approach	Si	Opportunities for new sediment remediation results, based on a holistic approach, using the specific experiences of each research group
Results of international importance	Si	If the techniques employed prove to be particularly advantageous (for example in terms of removal efficiency of certain contaminants, costs or simplicity of implementation and management) they would represent a model to be shared with the international scientific community for specific applications, or for more in-depth research.
Exchange of knowledge within the scientific community	Si	The results obtained, whether positive or negative, will in any case lead to the obtaining of information to share with the scientific community. If positive, they will open the way to new research and more efficient remediation opportunities; if negative, they will indicate that those techniques are not to be recommended for the treatment of certain contaminants.
Reuse of contaminated sediments	Si	Recycling of sediments into construction materials (cement materials, filler materials, foam concrete, etc.) for sustainable and cost-effective sediment treatment
	No	
	No	
	No	

➤ External Threats' selection

Table 4.13 Step 4 – External threats

<b>STEP 4 - Select the possible External Threats to include in the SWOT</b>		
<i>The analysis will be done for all SWOT factors</i>		
<i>You can add additional factors below the list</i>		
<i>Select Yes or No whether to include the field in Weaknesses - No limit on the number of selections</i>		
Check list	Include in SWOT (Si=Yes/No)	If Included in SWOT Report an Action
<i>Management of polluted and potentially environmentally hazardous material</i>	Si	<i>Implementation of an Environmental Monitoring Plan</i>
<i>Impact on navigation during construction activities</i>	Si	<i>Optimization of construction site activities in agreement with maritime authorities</i>
<i>Short-term and long-term impacts on existing sensitive ecosystems</i>	Si	<i>Implementation of an Environmental Monitoring Plan with short and long term monitoring</i>
<i>Large quantities of waste to manage</i>	Si	<i>Optimization of the final destination of the material in the process phase and of the management of the material on the construction site</i>
<i>High potential for complex management hot spots</i>	Si	<i>Monitoring of dredging activities with management of different scenarios</i>
<i>Unpreparedness of the executing company in managing complex matrices</i>	Si	<i>Request for technical requirements and qualifications of the executing company</i>
<i>Development of toxic or carcinogenic intermediates</i>	Si	<i>Certain chemical reactions can lead to the formation of toxic or carcinogenic intermediate products. The reactions must therefore be studied and monitored with precision, to overcome any critical issues.</i>
<i>Biomagnification phenomena due to suspended contaminants during dredging</i>	Si	<i>Suspension of contaminants is a frequent phenomenon during dredging operations. This could lead to an accumulation of contaminants in biological species that through the food chain (biomagnification) could also reach human receptors. To reduce these risks, containment techniques will be applied during dredging operations</i>
<i>Resuspension of contaminated particles resulting in CO2 emissions</i>	No	
	No	
	No	
	No	



➤ SWOT Analysis

Table 4.15 SWOT Analysis

SWOT analysis	
S	W
Deepening of port seabed to improve infrastructure efficiency	Limitations in management options
In-depth knowledge of the physical-chemical, <u>ecotoxicological and microbiological characteristics of</u>	Complexity of managing environmental processes
Knowledge of the chemical and ecotoxicological characteristics of the pollutants present	Lack of producers or operators of sediment treatment plants
Complete knowledge of the spatial distribution of potential biotic and abiotic targets of the emerged and	Presence of particular biocenoses in the surroundings of the dredging areasio
Extensive experience in managing dredging operations and port maintenance	Complex sediment management procedures
Appropriate size of dredge material management areas	Complex and difficult to control type of processing
Resilienza dei sistemi naturali, specialmente in ambienti fortemente antropizzati	Restriction of vessel traffic during dredging operations
Previous experience of research groups in the remediation of contaminated marine sediments	<i>High costs for remediation techniques based on thermal and chemical/physical processes Difficulty in finding</i>
	High costs and high environmental impact for the disposal of contaminated sediments in landfills
	Bioremediation treatments
O	T
Greater draft of the port seabed	Management of polluted and potentially environmentally hazardous material
Securing and remediating contaminated seabeds	Short-term and long-term impacts on existing sensitive ecosystems
Study of new remediation techniques through a holistic approach	Impact on navigation during construction activities
Job opportunities and creation of related industries	High potential for complex management hot spots
Results of international importance	Large quantities of waste to manage
Exchange of knowledge within the scientific community	Unpreparedness of the executing company in managing complex matrices
Reuse of contaminated sediments	Development of toxic or carcinogenic intermediates
	Biomagnification phenomena due to suspended contaminants during dredging

➤ Stock Analysis

Table 4.16 Stock analysis

SWOT Risk Action Analysis			
INTERNAL ANALYSIS			
Strengths (S)	Actions	Weaknesses (W)	Actions
Deepening of port seabed to improve infrastructure efficiency	Preparatory work for the correct development of port activities	Limitations in management options	Applications of multi-criteria decision making processes evaluating technical and economic aspects Implementation of a Site Specific Environmental Monitoring Plan
In-depth knowledge of the physical-chemical, ecotoxicological and microbiological characteristics of sediments	Complete characterization in accordance with current legislation	Complexity of managing environmental processes	Strengthen Know-How by crossing different professional figures and project experiences
Knowledge of the chemical and ecotoxicological characteristics of the pollutants present	Complete characterization in accordance with current legislation and verification of exceeding contamination thresholds	Lack of producers or operators of sediment treatment plants	Encourage local entrepreneurship to invest in remediation treatments
Complete knowledge of the spatial distribution of potential biotic and abiotic targets of the emerged and submerged compartment	Mapping of biocenoses and mapping of environmental protection areas (SIC/ZPS)	Presence of particular biocenoses in the surroundings of the dredging areas	Implementation of a Site Specific Environmental Monitoring Plan
Extensive experience in managing dredging operations and port maintenance	Multi-year management of port infrastructures with different logistical needs	Complex sediment management procedures	Foresee in the design phase all possible scenarios and critical issues during the management of dredging works
Appropriate size of dredge material management areas	Large areas potentially exploitable for direct or accessory processes	Complex and difficult to control type of processing	Use of proven dredging technologies that limit resuspension of material throughout the water column
Resilienza dei sistemi naturali, specialmente in ambienti fortemente antropizzati	Complex aquatic systems have their own bio-geo-chemical equilibria	Restriction of vessel traffic during dredging operations	Optimization of the dredging process by favoring techniques with significant flow rates
Previous experience of research groups in the remediation of contaminated marine sediments	Consolidated experience of research groups on the topic, to be used as a starting point for new and integrated research	High costs for remediation techniques based on thermal and chemical/physical processes Difficulty in finding multiple real contaminated marine sediments in a short time	Applications of eco-friendly and cost-effective strategies such as degradation of contaminants by microbial populations
		High costs and high environmental impact for the disposal of contaminated sediments in landfills	Search for alternative solutions to landfill disposal
		Bioremediation treatments	Risk of long treatment times. To optimize them, we will try to apply combined treatments (treatment train)
Opportunity (O)	Actions	External Threats (T)	Actions
Greater draft of the port seabed	Opportunity to increase naval traffic with an impact on the economic and social fabric of the territory	Management of polluted and potentially environmentally hazardous material	Implementation of an Environmental Monitoring Plan
Securing and remediating contaminated seabeds	Removal of those contaminated sediments that are potential sources of secondary contamination	Short-term and long-term impacts on existing sensitive ecosystems	Implementation of an Environmental Monitoring Plan with short and long term monitoring
Study of new remediation techniques through a holistic approach	Opportunities for new sediment remediation results, based on a holistic approach, using the specific experiences of each research group Creation of a new construction site providing job opportunities with repercussions on the economic and social sector of the area.	Impact on navigation during construction activities	Optimization of construction site activities in agreement with maritime authorities
Job opportunities and creation of related industries	If the techniques employed prove to be particularly advantageous (for example in terms of removal efficiency of certain contaminants, costs or simplicity of implementation and management) they would represent a model to be shared with the international scientific community.	High potential for complex management hot spots	Monitoring of dredging activities with management of different scenarios
Results of international importance		Large quantities of waste to manage	Optimization of the final destination of the material in the process phase and of the management of the material on the construction site
Exchange of knowledge within the scientific community	The results obtained, whether positive or negative, will in any case lead to the obtaining of information to share with the scientific community. If positive, they will open the way to new research and more efficient remediation opportunities; if negative, they will indicate that those techniques are not to be recommended for the treatment of certain contaminants.	Unpreparedness of the executing company in managing complex matrices	Request for technical requirements and qualifications of the executing company
Reuse of contaminated sediments	Recycling of sediments into construction materials (cement materials, filler materials, foam concrete, etc.) for sustainable and cost-effective sediment treatment	Development of toxic or carcinogenic intermediates	Certain chemical reactions can lead to the formation of toxic or carcinogenic intermediate products. The reactions must therefore be studied and monitored with precision, to overcome any critical issues.
		Biomagnification phenomena due to suspended contaminants during dredging	Suspension of contaminants is a frequent phenomenon during dredging operations. This could lead to an accumulation of contaminants in biological species that through the food chain (biomagnification) could also reach human receptors. To reduce these risks, containment techniques will be applied during dredging operations

### 1.1.1. FMEA ANALYSIS

The management of reclaimed sediment from dredge operation might be a valid solution to address the interdisciplinary approach to contaminated sediment movement in port the area. The main reasons limiting this practice are the high investment and operation costs and the public concerns related to potential human and environmental risks. At the same time, the occurrence in the treated matrix of contaminants of emerging concern (CECs), most of them still unregulated, may increase the public distrust due to their accumulation in the environment. CECs include not only organic compounds, but also microbial contaminants, among them antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs).

Therefore, it becomes fundamental to develop a human health and environmental risk assessment to identify the main hazards and hazardous events and to evaluate their occurrence (likelihood) and the magnitude (severity) of hazard impacts on the exposed receptors.

The identification of the hazardous events may be carried out by means of the Failure Mode and Effect Analysis (FMEA): a qualitative methodology able to identify failure modes and their effects on the system (leakage, breakage, release, reduction in the removal efficiency, etc), which can result in a worse quality of the final effluent with potential adverse effects on the environment and human health (Stamatis 2003). The results of this analysis are generally reported in a table in terms of descriptions of the identified failure modes and their consequences. This table represents the basis for the development of the methodology. According to eq. 1, the risk is defined as the product of the likelihood of occurrence of a failure mode and the severity of its consequences.

Due to the lack of quantitative data on failure occurrence and consequence parameters, a semi-quantitative approach was adopted following the standard FMEA methodology (Stamatis 2003). The risk was evaluated using the Risk Priority Number (RPN) calculated as  $RPN = SEV \times OCC \times DET$  Where SEV (Severity), OCC (Occurrence), and DET (Detection) are scored from one to 10 based on expert judgment.

The values are defined based on the opinions of interviewed experts.

Higher likelihood corresponds to higher OCC scores, higher severity to higher SEV scores, and lower detectability to higher DET scores

**Table 4.17** FMEA Risk Priority Number (RPN) assessment matrix. Green = low risk (1-125), orange = medium risk (126-250), red = high risk (251-500), purple = very high risk (>500)

Likelihood score, S <sub>1</sub>	Magnitude score S <sub>2</sub>									
	1	2-4	5-9	10-16	17-25	26-36	37-49	50-64	65-81	82-100
1 (negligible)	1	2-4	5-9	10-16	17-25	26-36	37-49	50-64	65-81	82-100
2 (minor)	2	4-8	10-18	20-32	34-50	52-72	74-98	100-128	130-162	164-200
3 (moderate)	3	6-12	15-27	30-48	51-75	78-108	111-147	150-192	195-243	246-300
4 (major)	4	8-16	20-36	40-64	68-100	104-144	148-196	200-256	260-324	328-400
5 (severe)	5	10-20	25-45	50-80	85-125	130-180	185-245	250-320	325-405	410-500
6 (critical)	6	12-24	30-54	60-96	102-150	156-216	222-294	300-394	390-486	482-600
7 (very critical)	7	14-28	35-63	70-112	119-175	182-252	259-343	350-448	455-567	574-700
8 (hazardous)	8	16-32	40-72	80-128	136-200	208-288	296-392	400-512	520-648	656-800
9 (very hazardous)	9	18-36	45-81	90-144	153-225	234-324	333-441	450-576	585-729	738-900
10 (catastrophic)	10	20-40	50-90	100-160	170-250	250-360	370-490	500-640	650-810	820-1000

Based on the calculated RPN values, risks are categorized as: low (RPN 1-125), medium (RPN 126-250), high (RPN 251-500), and very high (RPN >500).

Those failure modes with the highest value of SEV correspond to the most critical ones. For these, an in-depth analysis of the existing preventive safety measures must be carried out to evaluate the capacity of the system to return the plant to normal operation, and if necessary, further (preventive and mitigative) safety measures must be implemented. The described approach is a semi-quantitative methodology that can be useful for a first and rough risk assessment in the case of wastewater treatment trains, including options for reuse of reclaimed water as shown in the following section. It represents a first attempt to develop a Plan of optimal strategies for the management of dredged sediment in commercial Port.

➤ **FMEA Risk assessment in the case of management of contaminated sediment – A proposed methodology**

The FMEA analysis, in the **task 4.5.3**, was used to preliminarily identify and quantify the main risks connected to dredging operations and the management of contaminated sediments. The methodology was used to analyze all the phases of the project, from the initial planning up to the final checks, ensuring an overall vision of the criticalities and of the actions necessary to prevent and/or mitigate them.

In the section regarding planning, particular attention was placed on possible delays in obtaining permits and on errors in the chemical-physical characterization of sediments, since these aspects can generate additional costs and slow down the entire operational process. For example, the authorization process often involves a series of bureaucratic steps that if not managed in advance and with correct documentation, risk significantly postponing the works. Approximate laboratory analyses, furthermore, can lead to an incorrect classification of sediments, with consequences on the choice of remediation or disposal techniques and, ultimately, on the project's times and costs.

In dredging operations, it resulted the necessity of maintaining a high level of equipment maintenance and of controlling dispersions. Faults in dredges, due to poor maintenance or the use of uncalibrated instrumentation, can cause machine stoppage with consequent delays and environmental risks, especially on the open sea. In addition, the dispersion of contaminants during maneuvers is a relevant risk: leaks and accidental spills not only compromise the marine ecosystem, but also can translate into fines and work interruptions.

Another significant critical issue concerns the transport and temporary storage of sediments. Here the main danger is cross-contamination among batches with different degrees of contamination, often due to labeling and traceability that are not always rigorous. The analyses have also highlighted the importance of correctly designing temporary deposits, equipping them with adequate containment barriers and drainage systems, to avoid secondary contamination of groundwater or soil.

In the remediation treatment, attention is concentrated above all on the actual effectiveness of the technologies adopted (for example, biological or chemical processes). To obtain satisfactory results, pilot tests on a reduced scale and constant monitoring of critical parameters, such as pH, temperature, and concentration of nutrients, where microorganisms are involved, are needed. An incorrect dosage of chemical reagents, the poor calibration of equipment, or the underestimation of possible undesired reactions (formation of toxic by-products) can indeed nullify the remediation efforts.

The final phase of disposal or reuse of the sediments requires great attention so that no residual contaminations occur. If, for example, the sediments are used for coastal replenishment, it is fundamental to verify through strict analytical checks that dangerous contaminants are no longer present. In the case of landfill disposal or of other uses, shared protocols with the authorizing entities and a rigorous emergency plan in case of anomalies (such as the rupture of containment ponds) are needed.

In order to guarantee that the entire control system functions correctly, the FMEA moreover has also provided a final check, in which the data of the laboratories in charge of the analyses are compared. Putting into practice standard sampling procedures and participating in interlaboratory test circuits allows reducing the risk of incongruent results, a frequent cause of delays and disputes.

From the FMEA it emerged that the early adoption of some corrective actions allows significantly lowering the risk indices (RPN). An example is given by the punctual planning of authorizations and by the definition of a schedule: anticipating bureaucratic processes, equipping oneself with rigorous sampling protocols, and selecting qualified laboratories noticeably reduces the probability of delays or classification errors. In the same way, proceeding with the preventive maintenance of dredges, installing real-time control sensors, and training personnel to manage emergencies and sudden operational variations are key interventions to decrease the frequency and gravity of unforeseen events in the dredging phase.

At the end of the analysis, it was estimated that, with the full implementation of the suggested measures, the project may benefit from a substantial reduction of dead times and extra costs caused by machine stoppages, extraordinary interventions, or disputes. Other expected benefits include the containment of the risk of contaminant dispersion, with a consequent improvement of environmental and operator safety, as well as greater transparency and participation by the authorities and the local community, thanks to adequate communication and consultation plans.

The analysis provided an overall vision, not limiting itself to being only a map of risks and intervention prior-

In the following page, general assessment sheets based on the specific multi-risk analysis assessments are shown ([Table 4.18](#)).

Process	Subprocess	Potential Impact	SEV	Main Causes	OCC	Detection Method	DET	RPN	Recommended Actions	Responsible
Planning	Delay in obtaining permits	Possible penalties, extra costs, suspension of activities	7	Lengthy bureaucratic process, incomplete documentation	7	Monitoring of deadlines and schedule control	5	245	Define a detailed authorization plan and start procedures in advance	Contractor
Dredging	Dispersion of contaminants into the sea	Risk to water quality and potential sanctions	8	Leaks from tanks, accidental spills, poor maintenance	7	Periodic equipment checks and visual inspections	6	336	Improve maintenance controls and install containment systems	Contractor
Treatment	Ineffective biological technology	Persistence of contaminants and need for additional treatments	8	Incompatible microorganisms or unfavorable environmental conditions	7	Periodic chemical-biological analyses	6	336	Perform pilot-scale tests and optimize operating parameters (pH, temperature, nutrients)	Technical Manager
Transport / Storage	Cross-contamination between batches	Difficulty in differentiating contaminated sediments, leading to extra remediation costs	8	Lack of separate compartments and classification errors	6	Cross-checking of documents and field inspections	6	288	Implement rigorous protocols for material separation and traceability	Technical Manager
Disposal/Reuse	Residual pollution post-beach nourishment	Risk to the marine ecosystem and possible legal actions, requiring further treatments	8	Superficial analyses and mixing with inadequate materials	7	Pre-release chemical-physical and ecotoxicological checks	5	280	Strengthen controls and validation procedures before reuse or beach nourishment	Technical Manager

Table 4.18 FMEA Multirisk Analysis

Legenda:

1. **SEV = Severity.** Failure Effect Severity: How severe the failure effect is on the process (Range 1-10)
2. **OCC = Occurrence.** How likely is it that the failure will occur? (Range 1-10)
3. **DET = Detection.** How likely is it that the failure will be detected before it happens? (Range 1-10)
4. **RPN = Risk Priority Number.** Risk Priority Index: is the product of SEV x OCC x DET. (Range 1-1000)

#### ➤ 4.6 Validation Case Study: Application to a Mediterranean Port

To validate the risk governance methodology proposed in this deliverable, the integrated SWOT-FMEA protocol was applied to a representative commercial port located in the Mediterranean basin. This site serves as a significant test bed for the framework, involving a dredging plan for approximately 1.4 million m<sup>3</sup> of sediments characterized across 26 sampling stations.

While the general chemical-physical characterization presented in previous sections focused on the Port of Genoa ("Proof of Concept"), this specific risk assessment validation was conducted on this complementary case study to test the framework's robustness in a complex multi-stakeholder environment.

**Methodology and Expert Panel** The study adopted a multi-expert assessment approach involving five specialists (academic and technical experts) to ensure methodological transparency and reduce subjective bias. The analysis followed a specific integrated sequence:

**SWOT Mapping:** Identification of 24 key items (Strengths, Weaknesses, Opportunities, and Threats) specific to the port's operational context.

**Failure Mode Derivation:** Mapping of 12 specific failure modes (FM) linked to the SWOT items.

**Risk Prioritization:** Calculation of the Risk Priority Number (RPN) based on Severity, Occurrence, and Detection scores provided by the panel.

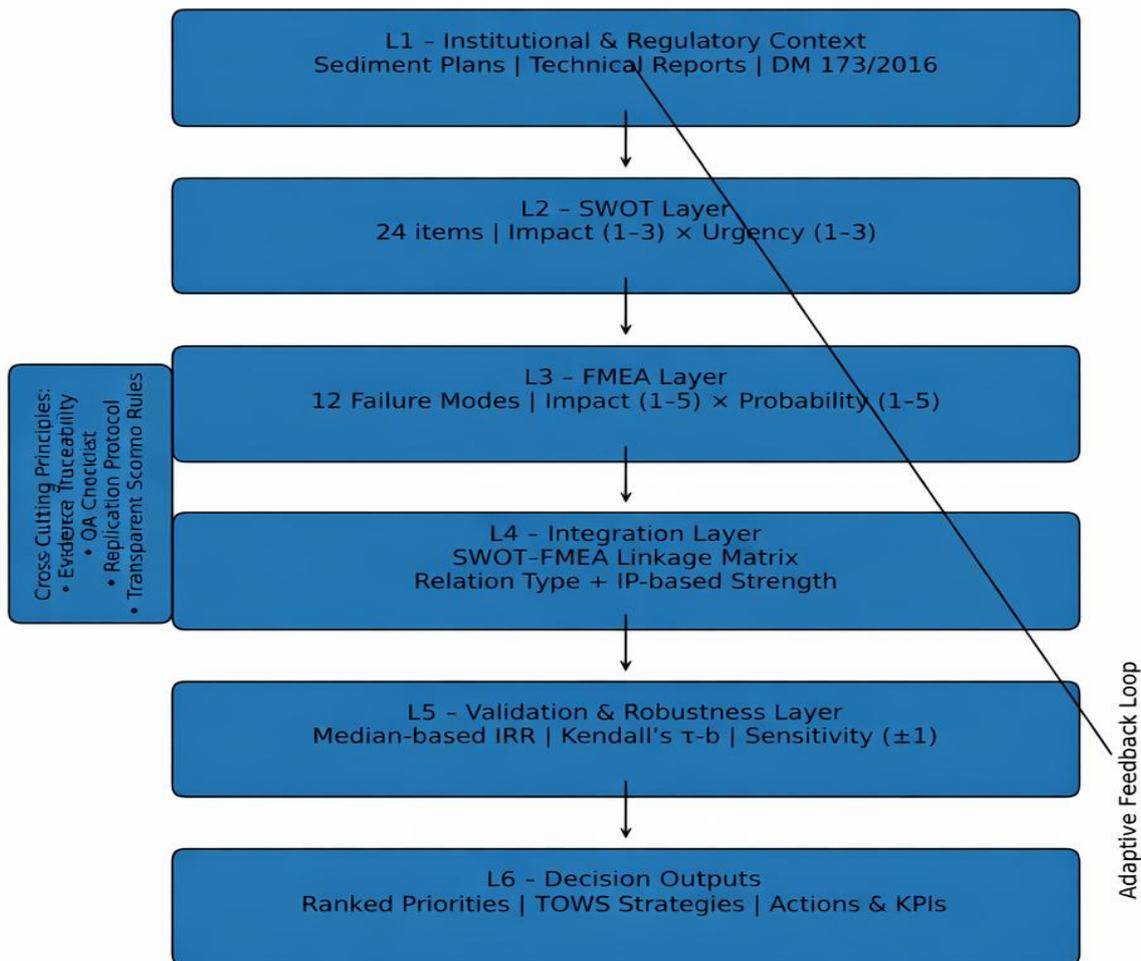


Figure 4.24 - Integrated SWOT-FMEA architecture showing the deterministic linkage operator. Strategic weaknesses are mapped to failure modes through "drives" relationships.

## ➤ Quantitative Results

The assessment highlighted that structural weaknesses in treatment infrastructure availability are the dominant risk drivers in this context, rather than purely chemical contamination issues.

Key Findings: The analysis identified "Lack of nearby treatment facilities" and "Uncertainty in disposal authorization" as top-priority risks.

Consensus: Inter-rater analysis revealed strong convergence among experts regarding infrastructure-related risks, while there was greater dispersion regarding environmental-operational uncertainties.

Sensitivity: The ranking proved stable (Kendall's  $\tau_b = 0.679-0.833$ ), confirming that the identified priorities are robust regardless of the aggregation method used (median vs. mean).

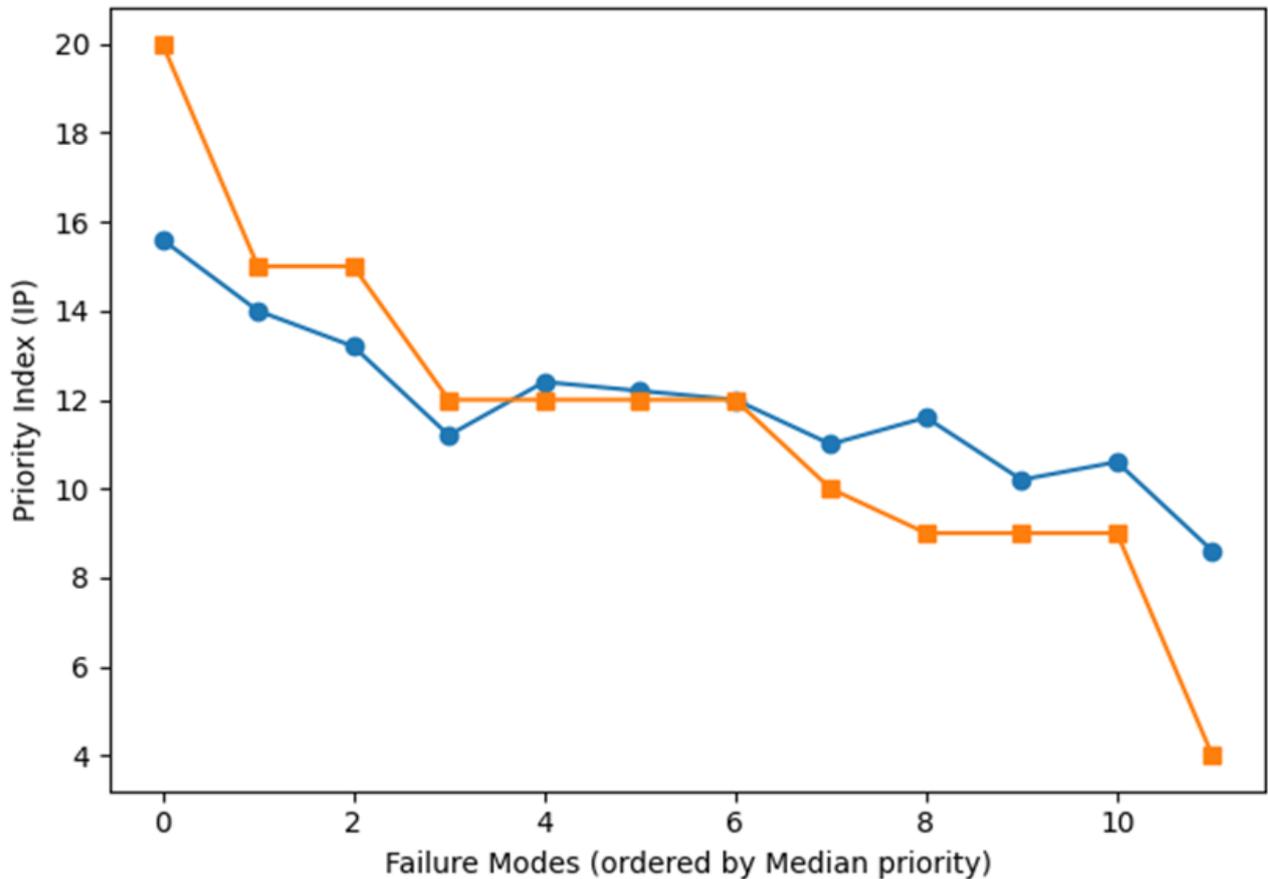


Figure 4.25 - Risk Priority heatmap (5 × 5 matrix) under median consensus, showing failure mode placement across Impact and Probability categories. Colour intensity indicates priority tier: green (Low,  $RP \leq 8$ ), yellow (Moderate,  $9 \leq RP \leq 15$ ), red (High,  $RP \geq 16$ ).

**From Analysis to Action: TOWS Strategies** The quantitative analysis was finally translated into actionable strategies for the stakeholders. The following Action Plan (Table 4.X) details the specific strategies derived from the risk assessment, identifying institutional owners, timeframes, and Key Performance Indicators (KPIs) to monitor the project's success.

ID	Type	Strategy	Owner	Timeframe	KPI
SO1	SO	Integrate seabed investigations to enable target draught and risk-based planning	Port Authority + Technical support	Short-Med	Operational plan adopted (Y/N)
SO2	SO	Leverage contaminant knowledge for risk-based sediment reuse routing	Port Authority + Supply chain	Medium	No. reuse options defined
SO3	SO	Capitalise on experience and staging areas for employment and R&D outcomes	Port Authority + University	Med-Long	Performance report produced (Y/N)
WO1	WO	Mitigate lack of treatment facilities via sediment valorisation and supply-chain agreements	Port Authority + Operators	Medium	Formal agreement signed (Y/N)
WO2	WO	Reduce hazardous fraction via innovative treatment to address disposal constraints	Port Authority + Operators	Medium	Final destination plan with option hierarchy (Y/N)
WO3	WO	Update characterisation data to minimise rework and delays	Port Authority + Labs	Short-Med	Data update plan implemented (Y/N)
ST1	ST	Use contaminant knowledge to manage hazardous material under evolving regulations	Technical support Authorities +	Short	EMP defined/approved (Y/N)
ST2	ST	Leverage seabed data to	Port Authority +	Short	Coordination plan adopted (Y/N)

ID	Type	Strategy	Owner	Timeframe	KPI
		mitigate weather impacts via operational coordination	Site management		
ST3	ST	Use staging areas and management capacity to handle waste volumes and hotspots	Port Authority + Operators	Medium	Waste/hotspot plan with alternative scenarios
WT1	WT	Reduce joint exposure to treatment-facility gap and regulatory tightening	Port Authority + Authorities	Short-Med	Supply-chain pathway qualified (Y/N)
WT2	WT	Manage sensitive biocenoses and ecosystem impacts via environmental monitoring	ARPA / Environmental consultants	Short	EMP with ecosystem indicators (Y/N)
WT3	WT	Address permitting complexity and contractor risk via technical requirements and QA/QC	Client + Contractor	Short	Technical requirements formalised; audits conducted (Y/N)

Table 4.19 TOWS action strategies with owners, timeframes, and KPIs

## PERFORMANCE AND COSTS OF INTERVENTIONS

The remediation of contaminated sediments represents a topic of paramount importance for environmental management, thanks to an approach that combines general evaluations based on literature and legislative parameters with site-specific assessments founded on chemical-ecotoxicological analyses of sediments and logistical considerations. The regulations governing sediment management suggest, in terms of priority, that reuse and recovery should come first. Among the multiple options, coastal nourishment, the reuse of material in construction, or habitat restoration carried out exclusively considering the dredged soil, follow. This direction contributes to the pillars of the circular economy: sediment is defined as a resource to be enhanced, not as waste.

Consequently, the choice of treatment technologies and the estimation of related costs primarily depend on the composition of the sediments and the nature of the pollutants.

In the case of moderate organic contamination, the literature highlights the effectiveness of biological treatments such as bioremediation, bioslurry, and mycoremediation, which generally have lower costs and a reduced environmental impact, although they require extended timeframes to achieve the objectives.

In cases of high organic contamination or contamination involving heavy metals, PFAS, or microplastics, it is often necessary to resort to physicochemical or thermal technologies, which are more expensive but also more effective for recalcitrant pollutants.

The effectiveness of these interventions depends on a series of pretreatments (dehydration, physical and granulometric separations) or the combination of multiple solutions (train treatment), with the aim of reducing the volumes of highly contaminated sediments, thereby optimizing the cost-benefit ratio.

The experiences documented in the literature and real cases highlight a notable variability in costs, attributable to site specificity, intervention scale, and the equipment required. Some studies indicate cost ranges, including various technologies and major management alternatives, as reported in the following [TABLE 4.20](#).

**Table 4.20** Cost range for major sediment remediation methods

Type of Intervention	Alternative Interventions	Costs
<b>Storage Interventions</b>	Discharge into the original water body, with deliberate immersion in offshore marine areas	5-10 €/m <sup>3</sup>
	Discharge into confined marine environments (containment basins, collection tanks), also sealed	5-35 €/m <sup>3</sup>
	Discharge into confined land environments	10-75 €/m <sup>3</sup>
	Seabed improvement through capping	3-5 €/m <sup>2</sup>
	Disposal in landfill	50-100 €/m <sup>3</sup>

<b>In-Situ Treatment Interventions</b>	Bioremediation, with the addition of microorganisms, nutrients, or ORC (Oxygen Release Compound)	15-30 €/m <sup>3</sup>
	Chemical precipitation	60-100 €/m <sup>3</sup>
<b>Ex-Situ Treatment Interventions</b>	Bioremediation with composting	35-60 €/m <sup>3</sup>
	Bioremediation with landfarming	25-45 €/m <sup>3</sup>
	Bioremediation with bioslurry reactors	80 €/m <sup>3</sup>
	Phytoremediation	15-30 €/m <sup>3</sup>
	Thermal desorption	50-70 €/m <sup>3</sup>
	High-temperature thermal treatments (incineration, pyrolysis, vitrification)	80-250 €/m <sup>3</sup>
	Solvent/chelating extraction (sediment washing)	70-130 €/m <sup>3</sup>
	Immobilization (solidification/stabilization)	50-110 €/m <sup>3</sup>
<b>Pre-Treatments</b>	Natural dewatering	10-25 €/m <sup>3</sup>
	Mechanical dewatering	20-35 €/m <sup>3</sup>
	Physical separation (sieving, hydrocyclones, etc.)	20-70 €/m <sup>3</sup>

The semi-bibliographic cost analysis indicates that in situ treatments are generally more economical, as they avoid the expenses associated with dredging and sediment transport, although they may not be suitable for deep or complex contamination. On the contrary, ex situ treatments offer greater control over sediment heterogeneity through separation, chemical reactions, or thermal processes, but require a higher initial investment.

Costs and timelines in this case are influenced by the distance of treatment plants, the presence of protected areas and/or regulatory constraints, and terrestrial or marine access.

In the Italian regulatory context, the emphasis on the priority of reuse and nourishment often directs interventions toward options compatible with the circularity of sedimentary resources, transforming them into potential secondary raw materials with the ultimate goal of reducing environmental impact, protecting public health, and, where possible, enhancing sediment as a resource, in line with the principles of sustainable development and recent circular economy policies.

## ONGOING RESEARCH AND FUTURE PROSPECTS FOR CONTAMINATED SEDIMENT MANAGEMENT

Based on the results obtained from the project activities, also taking into account the required TLR, some scenarios are addressed but not exhaustive.

For this reason, some topics considered fundamental for further study are currently underway or in the process of future programming (design and autonomous experiences).

- A. BIOSLURRY: analysis of rebound effects;
- B. SEDIMENT WASHING (SW): the combined use of ferrate and surfactants for the abatement of mercury and inorganic substances
- C. Study of thermal desorption at low temperatures with the use of solar condensers and for remediation of sediments contaminated by mercury
- D. In-situ mycoremediation: batch laboratory tests to evaluate its feasibility DA AGGIUNGERE
- E. In-depth study of the production of off-gas and abatement methods, using recycled material (for example biochar from biomass pyrolysis)

In particular, the sediments from the port of Genoa contaminated with TPH were treated according to two types of treatment: Bioslurry and SW

A - The **biological "bioslurry"** treatment was conducted by means of autochthonous microorganisms, already present within the contaminated sediments, assisted by an inoculum of activated sludge adapted to the salinity. The experimental campaign involves four batches (R1, R2, R3, R4), each with a working volume of 4 liters, a sediment/water ratio of 10% by weight (%wt), and operating in parallel for a total period of 60 days. In order to evaluate possible "rebound" effects of the TPH present in the contaminated sediments, a seawater exchange was performed every 15 days in reactors R2, R3, and R4 according to the operating conditions reported below:

- **R1:** Inoculum of activated sludge + 400 g of contaminated sediment + 4000 g of seawater. The reactor is maintained in batch mode for the entire duration of the experiment.
- **R2:** Inoculum of activated sludge + 400 g of contaminated sediment + 4000 g of seawater. The reactor is maintained in batch mode for the entire duration of the experiment. However, every 15 days, a mass of fresh seawater equal to 25% by weight (%wt) of the slurry was exchanged.
- **R3:** Inoculum of activated sludge + 400 g of contaminated sediment + 4000 g of seawater. The reactor is maintained in batch mode for the entire duration of the experiment. However, every 15 days, a mass of fresh seawater equal to 50% by weight (%wt) of the slurry was exchanged.
- **R4:** Inoculum of activated sludge + 400 g of contaminated sediment + 4000 g of seawater. The reactor is maintained in batch mode for the entire duration of the experiment. However, every 15 days, a mass of fresh seawater equal to 75% by weight (%wt) of the slurry was exchanged.

At the beginning and end of the batch tests, liquid-liquid and solid-liquid extractions of TPH were performed to evaluate the hydrocarbons removal efficiency. This is expected to be predominantly biological TPH removal and, to a lesser extent, physical TPH removal (i.e. mainly associated with stripping phenomena). The potential "rebound" effect in reactors R2, R3, and R4 should be associated with the concentration gradient between the contaminated sediment and the liquid bulk. This concentration gradient is expected to increase as the mass percentage of the exchanged seawater increases.

B - The study of the **chemical/physical "sediment washing"**, using oxidizing agents (i.e., potassium ferrate, potassium permanganate) and an anionic surfactant (Sodium Dodecylbenzenesulfonate, SDBS), consists of performing a series of batch tests. The purpose of these tests is to evaluate the extraction capacity of the oxidants and the anionic surfactant on the contaminants present in the sediment. The batch tests are performed in 1 L beakers using the equipment commonly employed for Jar Tests.

- o The experimental campaign involves conducting the following batch tests:

**Tests with potassium permanganate** on 100 g of contaminated sediments and 500 mL of Milli-Q water. Operating conditions:

- 0.5% wt potassium permanganate; 0% wt SDBS;
- 0.5% wt potassium permanganate; 0.1% wt SDBS;
- 0.5% wt potassium permanganate; 0.2% wt SDBS;
- 0.5% wt potassium permanganate; 0.4% wt SDBS;
- 1% wt potassium permanganate; 0% wt SDBS;
- 1% wt potassium permanganate; 0.1% wt SDBS;
- 1% wt potassium permanganate; 0.2% wt SDBS;
- 1% wt potassium permanganate; 0.4% wt SDBS;
- 1.5% wt potassium permanganate; 0% wt SDBS;
- 1.5% wt potassium permanganate; 0.1% wt SDBS;
- 1.5% wt potassium permanganate; 0.2% wt SDBS;
- 1.5% wt potassium permanganate; 0.4% wt SDBS;
- 2% wt potassium permanganate; 0% wt SDBS;
- 2% wt potassium permanganate; 0.1% wt SDBS;
- 2% wt potassium permanganate; 0.2% wt SDBS;
- 2% wt potassium permanganate; 0.4% wt SDBS;

**Tests with potassium ferrate** on 100 g of contaminated sediments and 500 mL of Milli-Q water. Operating conditions:

- 0.5% wt potassium ferrate; 0% wt SDBS;
- 0.5% wt potassium ferrate; 0.1% wt SDBS;
- 0.5% wt potassium ferrate; 0.2% wt SDBS;
- 0.5% wt potassium ferrate; 0.4% wt SDBS;
- 1% wt potassium ferrate; 0% wt SDBS;
- 1% wt potassium ferrate; 0.1% wt SDBS;
- 1% wt potassium ferrate; 0.2% wt SDBS;
- 1% wt potassium ferrate; 0.4% wt SDBS;
- 1.5% wt potassium ferrate; 0% wt SDBS;
- 1.5% wt potassium ferrate; 0.1% wt SDBS;
- 1.5% wt potassium ferrate; 0.2% wt SDBS;
- 1.5% wt potassium ferrate; 0.4% wt SDBS;
- 2% wt potassium ferrate; 0% wt SDBS;
- 2% wt potassium ferrate; 0.1% wt SDBS;
- 2% wt potassium ferrate; 0.2% wt SDBS;
- 2% wt potassium ferrate; 0.4% wt SDBS;

A control test with 0%wt of chemical oxidant and 0%wt of SDBS was conducted.

From an operational point of view, each batch test is conducted as follows:

- Add the SDBS (where applicable);
- Activate rapid mixing for 5 minutes at 200 rpm;
- Reduce the mixing intensity to 90 rpm and maintain it for 48 hours;
- 24 hours after the start of each test, add the chemical oxidant, which will act for the subsequent 24 hours;
- Monitor the pH throughout the test period;
- After 48 hours, the test is stopped, followed by 1 hour of sedimentation/solid-liquid separation.

At the end of each batch test, the following steps must be performed:

- Collect the liquid phase and filter it using a vacuum pump and a 0.45-micron filter;
- The liquid samples are stored in a refrigerator for subsequent liquid-liquid TPH extraction;
- The solid residues are collected in aluminium trays and left to dry in an oven at 30°C for 24 hours. Subsequently, a solid-liquid TPH extraction will be carried out.
- The extracted TPH samples will be analysed by GC-FID.
- Preserve 10 g (dry weight) for the solid-liquid extraction and approximately 40 g (dry weight) of the post-treatment sediment to perform germination tests in order to evaluate the potential for agronomic reuse of the recovered sediment.
- Although the target contaminants are TPH, the potential presence and removal of mercury from the solid phase will also be investigated.

C - TD has showed effectiveness as remediation treatment for TPH contaminated sediments. For these organic pollutants, heat treatment simulated through laboratory-scale plant (a tubular furnace) was highly effective at low temperatures (less than 300°C), regardless of the contamination level of the solid matrix. However, the applicability of TD can also be extended to an inorganic contaminant such as mercury, requiring for this pollutant the achievement of slightly higher temperatures (350°C), however falling within the range of LTTD (Low Temperature Thermal Desorption). The required target temperature leads to greater energy consumption at the end of the remediation treatment. Considering that in TD real plants energy needs are usually guaranteed by the use of fuels (such as natural gas, LPG), research studies will be conducted to identify a less impactful and more sustainable solution in terms of carbon footprint due to the emissions generated by fossil fuels. Among the most innovative solutions is that of concentrating solar system, such as Parabolic Trough Collectors. By transforming a renewable source such as solar energy into thermal energy via heat transfer fluid, concentrating solar power systems do not create an impact in terms of greenhouse gas emissions for TD treatment, and allow the environmental sustainability criteria established by the European Union to be met. The application of the ex-situ configuration treatment for the remediation of sediments will be related to a technological system, which, by exploiting solar radiation, converted into thermal energy, will guarantee the achievement of the target temperatures for the removal of mercury from sediments. The evaluation can be preliminarily conducted via Computational Fluid Dynamic (CFD) software, such as Ansys Fluent, with the aim of performing a scale-up of the system through a pilot plant. Specifically, new analysis concern:

- the local intensity of solar radiation;
- the type of heat transfer fluid, commonly synthetic oils allow high temperatures to be reached (around 400°C);
- the materials used for the connecting elements of the solar concentrating system with that of TD.
- The sediments characteristics, with particular attention to water content, which represents an important rate of energy, needs to reach target temperature.
- Preliminary modelling studies will therefore have the aim of identifying and optimizing the whole system through these factors, so that the evaluation would be extended to a case study involving the remediation of real mercury contaminated sediments.

D - Within the PNRR RETURN Partnership and in collaboration with Researchers working in the Project SUS-MIRRI, preliminary experimental tests have been carried out on the feasibility of mycoremediation for the treatment of contaminated marine sediments. This activity is developed synergically with the activities carried out under the RETURN TASK 4.5.2 “Development of innovative and ecofriendly bioremediation technologies”; therefore, all the details about this activity are reported into the final Delivery of Task 4.5.2.

Briefly, as discussed above, the study is aimed to assess the effectiveness of mycoremediation in a bioslurry system treating hydrocarbon-contaminated marine sediments, comparing different operational strategies, including the use of biochar as a fungal support material. Experimental activities were carried out in a laboratory – scale bioslurry system. The experimental campaign, with a total duration of 60 days and currently ongoing, was conducted using a laboratory-scale bioslurry apparatus consisting of four parallel reactor lines (Figure 4.26).

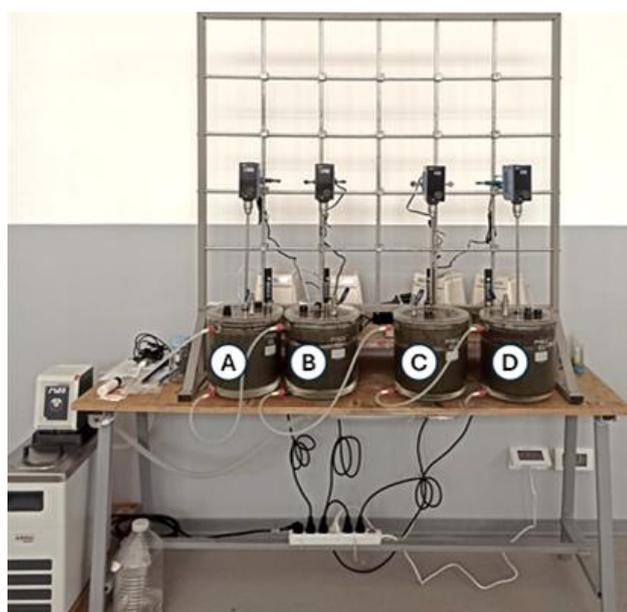


Figure 4.26 - Panoramic view of the experimental apparatus.

The four reactor configurations were as follows: (A) abiotic control, with sodium azide added to inhibit microbial activity; (B) biotic control, containing native microbial communities; (C) mycoremediation system with fungal inoculation; and (D) enhanced mycoremediation system with fungal biomass immobilized on biochar.

Marine sediments collected from the Port of Genoa were artificially contaminated with diesel fuel at 1% (w/w), resulting in an initial TPH concentration of approximately 5000 mg kg<sup>-1</sup> dry solids. Prior to experimentation, sediments were homogenized for 15 days to allow volatilization of lighter fractions, dried at 40°C for 72 h, and subsequently ground and sieved to <2 mm. The biochar used (B440) was produced from woody biomass derived from pruning residues at the University of Palermo.

Autochthonous fungal strains were selected through functional screening assays and are preserved in the CoID Culture Collection (University of Genoa). Fungal inocula were prepared by culturing biomass on specific media at 24°C for three weeks, followed by suspension in sterile seawater and standardization to conidial concentrations  $\geq 10^6$ .

An integrated monitoring protocol was adopted to assess the microbiological, chemical, and environmental evolution of the system over time. Mycological analyses were performed biweekly in reactors C and D to assess fungal viability and abundance. Direct examinations, reinoculation of sediments on plates, and isolation of colonies grown after 7 days were used both to verify inoculum viability and to quantify fungal presence. In reactor D, where fungal colonies were immobilized on biochar, scanning electron microscopy (SEM) analyses were conducted to investigate biochar colonization, biological immobilization, and mycelial morphology, and to correlate these features with system performance. At

the same time intervals and in all lines, TPH concentrations were measured in both liquid phase and solid phases using standardized analytical methods: “Oil Index”, UNI EN ISO 9377-2 and “Procedure for the analysis of hydrocarbons >C12 in contaminated soils – Manuals and Guidelines 75/11”, ISPRA, 2011, respectively. Moisture content, required for solid – phase TPH calculations, was determined according to Official Method no. II.2., Suppl. Org. G.U. no. 248 of 21/10/99. Additionally, key process parameters, including dissolved oxygen, pH, temperature, and electrical conductivity, were monitored twice weekly. Volatilized hydrocarbons (VOC) emissions were quantified using a portable flame ionization detector (FID) coupled with a hot-wire anemometer for the off-gas flow measurements. At the end of the experiment, residual phytotoxicity was assessed using a germination index test on *Lepidium sativum* (garden cress), following the APAT (2004) procedure.

The experimental activity is still ongoing, and a significant portion of the acquired data is currently under analysis; therefore, only preliminary results related to TPH removal and fungal biochar colonization are reported below.

### ***Fungal Colonization of Biochar: Temporal Dynamics Observed by SEM***

SEM micrographs (Figure 4.27) reveal a significant temporal dynamic in fungal colonization of the biochar. Biochar not exposed to fungal colonies (Figure 4.27a) shows a well-defined porous structure typical of pyrolyzed lignocellulosic materials, characterized by elongated channels, open cellular cavities, and layered walls. After 48 hours of incubation, images (Figure 4.27b) show a network of branched filaments and numerous spheroidal particles associated with the biochar surface, consistent with hyphal and conidial development, demonstrating rapid substrate colonization. This behaviour aligns with literature reports indicating that biochar can promote microbial adhesion due to its porosity and capacity to provide protected microhabitats (Yin et al., 2023). After 21 days, SEM images (Figure 4.27c) no longer show a widespread filamentous network on the surface; instead, the biochar surface appears more exposed, with original pores and channels preserved. The reduced presence of hyphae and conidia may suggest several interpretations, including loss of organism viability due to stressful reactor conditions. Further investigations are ongoing.

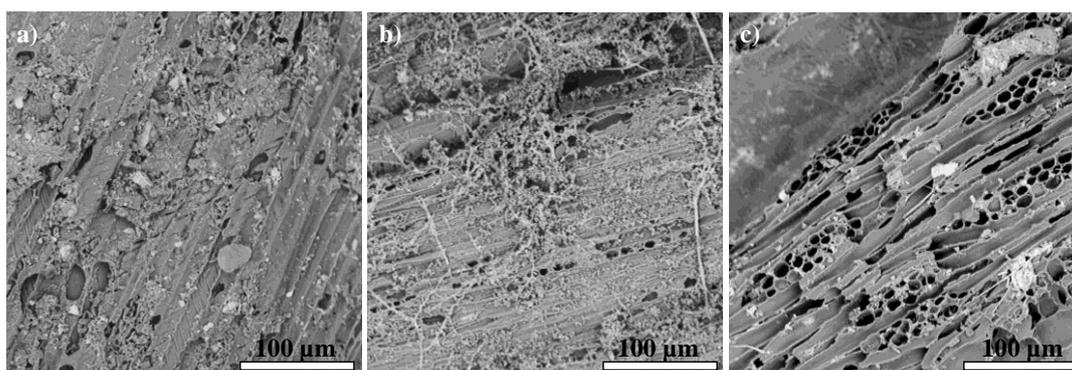


Figure 4.27 - SEM images of biochar before contact with fungal colonies (A), 48 hours after contact (B), and after 21 days of experimentation (C)

### ***TPHs removal efficiencies***

After the first two weeks of experimentation, TPH concentration in the abiotic control (reactor A) decreased by 23% (residual concentration in sediment: 2855 mg/kg), likely due to desorption and volatilization phenomena. In the biotic control (reactor B), TPH reduction was significantly higher at 41% (2205 mg/kg), confirming the contribution of aerobic biodegradation by the autochthonous microbial community. In reactors C and D, where mycoremediation was applied, TPH removal reached approximately 55% (residual concentrations in both lines around 1675 mg/kg). The activities are still ongoing. Nevertheless, the first results are encouraging, highlighting the potential role of fungi in enhancing bioremediation processes in marine sediments.

During the RETURN project, the UniGe research group, in collaboration with colleagues from the UniGe PNRR SUS-MIRRI project, began applying mycoremediation techniques to sediments collected from the ports of Genoa and Augusta. To increase the pollution load and better highlight the bioremediation capacity of microfungi, a known quantity of diesel fuel was added to the sediment.

The mycoremediation technique, already used for a long time for terrestrial sediments, is also applied to sediments dredged from port areas: UniGe's DISTAV has carried out several Interreg Maritime ITA-FR 2014-2020 projects specifically on these topics (SEDITERRA, GEREMIA, and QUALIPORTI, a project primarily focused on mycoremediation of the water column above the sediments).

For RETURN, below we indicate the activities carried out (activities still in progress), which will provide the next results by the end of the project.

Two sediment samples were taken from the seabed of the Port of Genoa (samples 1 and 2). The sand was left to settle for half an hour, and 100  $\mu$ L of seawater was collected from each sample. The water was then placed onto three 90-mm Rose Bengal with sterile seawater (RBm) and three Malt Extract Agar with sterile seawater (MEAm) plates, and incubated in the dark at 24 °C (Tab.4.21).

<b>1</b>	3 MEA mare	1A	1B	1C
	3 RB mare	1A	1B	1C
<b>2</b>	3 MEA mare	2A	2B	2C
	3RB mare	2A	2B	2C

Table 4.21 Number of plates inoculated with seawater from each sample.

One gram of sand of each sample was diluted by factors of 10, 100, and 1000 in sterile water. The resulting solutions were then inoculated onto three 90-mm Rose Bengal (RBm) with sterile seawater and three Malt Extract Agar (MEAm) with sterile seawater plates, incubated in the dark at 24 °C (Tab.4.22).

<b>1</b>	10	3 MEA mare	1A	1B	1C
		3 RB mare	1A	1B	1C
	100	3 MEA mare	1A	1B	1C
		3 RB mare	1A	1B	1C
	1000	3 MEA mare	1A	1B	1C
		3 RB mare	1A	1B	1C
<b>2</b>	10	3 MEA mare	2A	2B	2C
		3 RB mare	2A	2B	2C
	100	3 MEA mare	2A	2B	2C
		3 RB mare	2A	2B	2C
	1000	3 MEA mare	2A	2B	2C
		3RB mare	2A	2B	2C

Table 4.22 Number of plates inoculated with diluted solutions from samples one and two.

After seven and fourteen days, fungal growth was detected on 11 out of 48 plates (Fig.4.28).

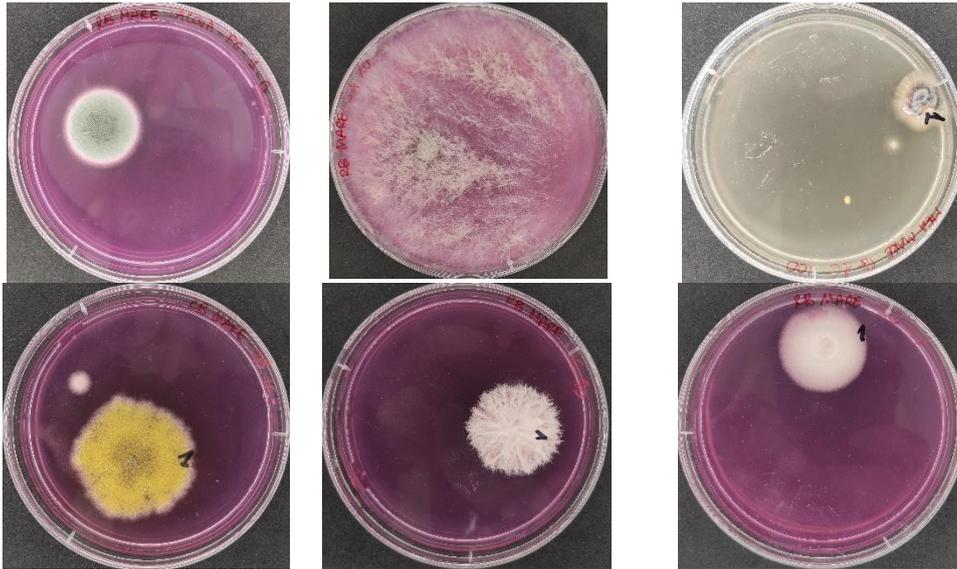


Figure 4.28 - Some Petri dish with fungal growth

Fungal colonies that had grown were isolated in pure culture on MEA (Fig.4.29). The strains were cryopreserved in cryovials containing nutrient broth and sterile 30% glycerol, and deposited in the Cold UNIGE JRU MIRRI-IT collection.

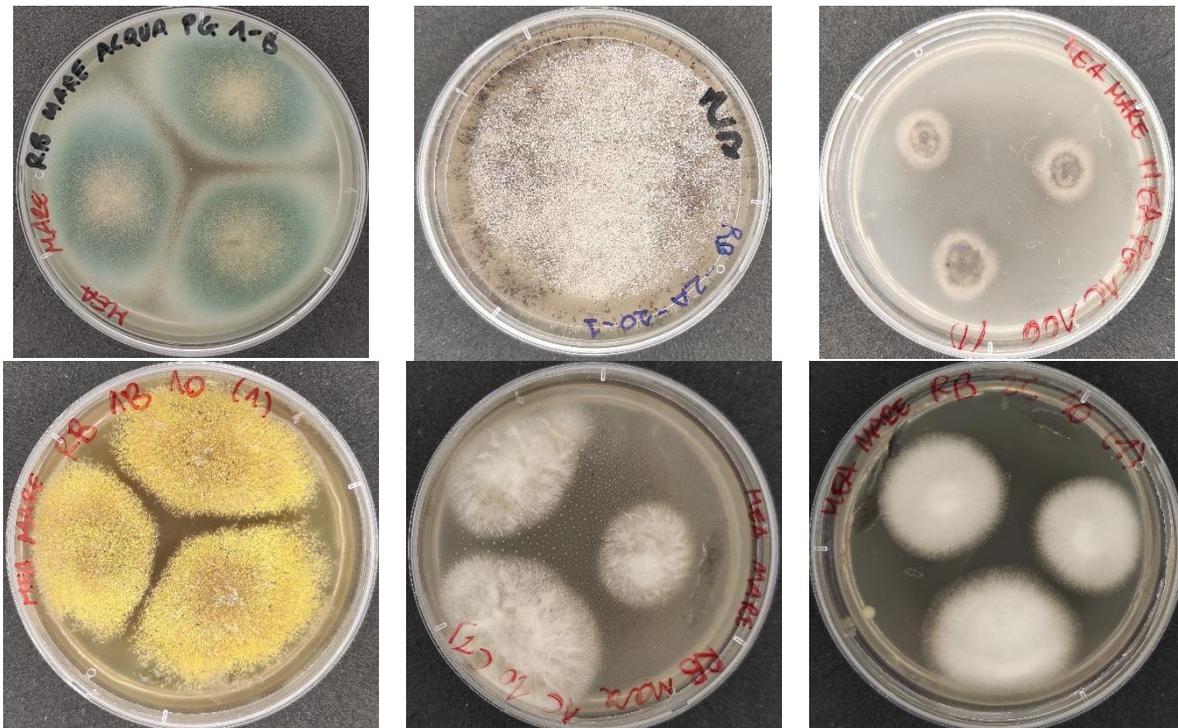


Figure 4.29 - Pure cultures isolated from Petri dish listed in Table 4.28.

Slides were prepared from the isolated pure cultures and observed under an optical microscope (Fig.4.30).

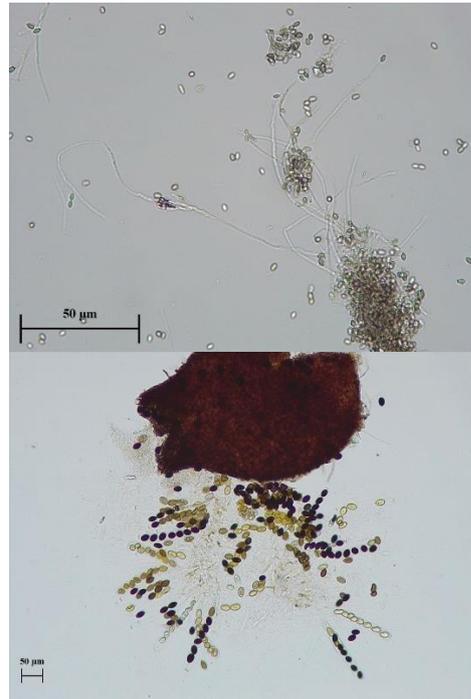


Figure 4.30 - Microscopic view of some isolated fungi.

## GENERAL CONCLUSION ON PROOF OF CONCEPT

### BETTER PERFORMANCE FOR SPECIFIC APPLICATION (BIOLOGICAL, PHYSICAL AND CHEMICAL PROCESSES)

It is not easy to define a "best technology" for sediment remediation: generally speaking, optimal performance, in purely analytical terms, is that which adapts to the site-specificity of the sedimentary matrices and the actual contamination level (medium-high-critical). In this regard, it's often useful to consider supply chain or train-treatment.

In general, choosing the best technology for the remediation of contaminated marine sediments in terms of performance (defined as contaminant removal/reduction effectiveness and response times) depends crucially on the type and concentration of contaminants (organic, inorganic, heavy metals), the characteristics of the sediments (grain size, organic content, water content), and the site's remediation objectives. Technologies are divided into two main categories:

- **Ex Situ Technologies:** These involve the removal (dredging/excavation) of contaminated sediments, followed by treatment in a facility (on-site or off-site) and subsequent disposal or reuse of the treated material.
- **In Situ Technologies:** Contaminant treatment or isolation occurs directly on-site, without removing the sediment.

### Ex Situ Technologies (High Efficiency)

These technologies, although more expensive and complex due to the need for dredging, tend to offer the best performance in terms of removal or complete destruction of contaminants, especially in the presence of high concentrations and mixed contamination.

Technology	Process	Performance and Key Benefits
<b>Thermal Desorption</b>	Heating of sediments to volatilize organic contaminants (hydrocarbons, VOCs, SVOCs), which are then collected and destroyed or treated.	Extremely effective against volatile and semi-volatile organic contaminants. Rapid response times.
<b>Soil Washing / Sediment Washing</b>	Physical and/or chemical separation of contaminants from sediments, taking advantage of the fact that pollution is concentrated in the finest particles (silt and clay).	Very effective for removing heavy metals and some organic contaminants. Allows for the recovery of the clean sand fraction.
<b>Chemical Oxidation</b>	Physical and/or chemical separation of contaminants from sediments, taking advantage of the fact that pollution is concentrated in the finest particles (silt and clay).	Effective for a wide range of organic contaminants (e.g. hydrocarbons), with relatively short times.
<b>Sifting</b>	Granulometric separation, often as a pre-treatment for soil washing.	Very effective for reducing the volume of material to be treated, concentrating the contaminants in the fine fraction.
<b>Mycoremediation</b>	Removal of pollutants from the sediment by accumulation in the microfungi (heavy metals) and reduction of complex hydrocarbon molecules into sugars	At the moment the mycoremediation of the dredged sediments is in the micro- and meso-cosm phase but the results are encouraging

More versatile technologies are often preferred for their environmental sustainability and lower costs (they do not require dredging), but they can have longer response times and variable effectiveness, especially for more severe contamination.

Technology	Process	Performance and Key Benefits
<b>Solidification/Stabilization (S/S)</b>	Addition of binders (e.g. cement) to physically and chemically immobilize contaminants in the sediment, reducing their mobility and toxicity.	Very effective for heavy metals and inorganic contaminants. Allows for permanent in-situ containment.
<b>Bioremediation</b>	Stimulation of the activity of indigenous microorganisms to degrade organic contaminants into harmless compounds.	Effective on biodegradable organic contaminants (e.g., hydrocarbons). A natural, economical, and low-impact process, but it requires a long time. It can be combined with electrokinetics to increase its effectiveness.
<b>Monitored Natural Attenuation (MNA)</b>	Monitoring of natural processes (adsorption, sedimentation, biodegradation) that spontaneously reduce the toxicity and bioavailability of contaminants.	A low-cost, minimal-impact option. Suitable for low-concentration contamination or when natural processes are very rapid.
<b>Underwater Capping (Confinement)</b>	Placing a layer of clean material (sand, gravel, geosynthetics) over the contaminated sediments.	Highly effective in preventing the dispersion and exposure of contaminants (physical isolation). Quick and often economical. It isolates the contamination rather than removing it.

## IMPACT OF DREDGING AND RELEASE INTO THE SEA: HYDRODYNAMIC ASPECTS AND MONITORING PLANS

Dredging and sediment release into the sea (submersion) are complex operations that generate significant impacts on the marine environment, particularly on hydrodynamics and water quality. Managing them requires rigorous monitoring plans.

### Hydrodynamic Impact of Dredging and Release

The main impact is related to sediment resuspension and the creation of turbidity plumes.

#### ➤ Dredging Effects (Removal)

Dredging, especially in operations on contaminated seabeds (environmental dredging), must minimize sediment removal and resuspension.

- **Resuspension of Contaminants:** The removal of sediment, especially fine-grained sediments (silt, clay), can cause the resuspension of finer particles, to which most contaminants (heavy metals, organic compounds) bind. These contaminants can be released into the water column, increasing their bioavailability and toxicity to marine organisms.
- **Altered Morphobathymetry:** Excavation changes the seabed depth, potentially altering current and wave patterns, with effects on coastal stability and local sediment dynamics.
- **Turbidity:** Increased turbidity reduces light penetration into the water, negatively impacting photosynthetic organisms, such as *Posidonia oceanica* meadows.

➤ Effects of Release into the Sea (Immersion)

The release of dredged material (if permitted by regulations based on sediment quality) has distinct hydrodynamic effects:

- **Release and Dispersion:** The material, often released into the water as a fluid suspension, generates a turbidity plume that disperses through advection (transport by currents) and diffusion. The fate of this material is dictated by the particle settling velocity and the hydrodynamic circulation of the area.
- **Accumulation and Seabed Modification:** In the release zone, the material settles, modifying the bathymetry and seabed composition, potentially suffocating benthic biocoenoses.

To predict impacts, the use of mathematical and numerical models capable of simulating the generation and transport of turbidity plumes in relation to hydrodynamic characteristics (currents, tides, wave motion) and sediment grain size is essential.

### **Environmental Monitoring Plans (EMP)**

An Environmental Monitoring Plan (EMP) is an essential and dynamic tool, required by legislation (e.g., Ministerial Decree 172/2016 in Italy for SINS), to verify environmental impacts and the effectiveness of mitigation measures.

EMPs are generally structured in three phases:

➤ 1. Ante Operam (Pre-Intervention) Monitoring

This serves to define the environmental baseline before the start of operations.

- **Hydrodynamic Parameters:** Detection of currents, wave motion, and tides.
- **Water and Sediment Quality:** Measurement of contaminant concentrations and chemical-physical parameters (temperature, salinity, dissolved oxygen).
- **Sensitive Ecosystems:** Mapping and characterization of valuable habitats (e.g., Posidonia oceanica meadows, coralligenous areas).

➤ 2. On-going Monitoring (During the Intervention)

This aims to detect impacts in real time or near real time, allowing for timely corrective measures.

- **Turbidity and Total Suspended Matter:** Continuous or high-frequency measurements (via multiparameter probes or buoys) of turbidity in the water column, especially near the dredging area and sensitive targets.
- **Operational Control:** Monitoring of operational parameters (e.g., dredging speed, equipment tightness) to minimize resuspension.
- **Contaminants (Optional):** Targeted sampling to assess the potential release of dissolved contaminants.

➤ 3. Post-Operation Monitoring

This serves to verify the achievement of remediation objectives and the trend toward restoring initial environmental conditions.

- **Hydrodynamic Restoration:** Verification of the stabilization of currents and the morphological reorganization of the seabed (especially in the submerged area or in the case of capping).
- **Environmental Quality:** Repeated water and sediment analyses to verify the reduction of contaminants and the absence of long-term effects.
- **Biological Recovery:** Evaluation of seabed recolonization and the health of sensitive biocoenoses.

BETTER RECOVERY/REUSE CHOICES (ENVIRONMENTAL BENEFITS)

The best options for recovery/reuse (beneficial use) of decontaminated or remediated marine sediments are those that promote the circular economy and offer the greatest environmental benefits, reducing the need to extract new natural resources. The final choice depends on the particle size characteristics and chemical quality.

➤ Coastal Replenishment and Coastal Defence

This is the reuse with the greatest and most direct marine environmental benefit, provided the sediments are predominantly sandy and of high quality (or decontaminated to levels compatible with the marine-coastal environment).

- **Environmental Benefits**
- **Coastal Erosion Prevention:** Provides suitable material for rebuilding eroded beaches, protecting the shoreline and infrastructure from sea advance.
- **Functional Restoration:** Restores the balance of coastal dynamics and natural habitats (emergent and submerged beaches), unlike rigid structures (piers, groynes) that can alter sediment transport.
- **Ecosystem Protection:** If the material has grain size characteristics similar to the original, it promotes the recovery of benthic organisms and the functionality of the coastal environment.

Civil Engineering and Port Infrastructure

Use in infrastructure and land-based settings is the primary choice for sediments that are unsuitable for beach nourishment, often because they are too fine (silty/clayey) or due to their geotechnical properties.

Use Options

Usage	Typical Material	Environmental Benefits
<b>Port Fills and Embankments</b>	Sand and gravel, or treated and consolidated sludge.	It allows for the expansion of port areas, the construction of docks, and the creation of landfill sites (confined structures) in which to deposit the dredged material, avoiding disposal in landfills or in the open sea.
<b>Building Materials</b>	Separated and treated sandy or clayey fraction.	The clay fraction can be used in the production of bricks (e.g. bricks), while the sand and gravel can be used as aggregates for concrete or road bases, reducing extraction from land-based quarries.
<b>Capping (Seabed Covering)</b>	Clean sediment (often the sandy fraction).	Used to create an insulating layer ("hood") over unremoved contaminated sediments, isolating them from the water column and marine organisms.

➤ Environmental and Landscape Restoration

Use Options

These uses aim to restore degraded areas or improve soil conditions.

- **Agricultural Improvement and Techno-Landscapes:** Fine sediment (silt and clay) can be used, after appropriate treatments (e.g., mixing with organic amendments), as techno-soil to improve the properties of degraded soils or for revegetation and landscape restoration projects.
- **Habitat Restoration (Biological Remediation):** Decontaminated sediments can be reintroduced into wetlands or lagoons to restore morphology and support local ecosystems, including remediation through natural techniques (e.g., phytoremediation) that use plants to stabilize and further remediate the matrix.

➤ Overall Benefits of Reuse

The reuse of dredged and treated sediment, in line with the principle "sediment is a resource," offers crucial benefits:

- **Conservation of Natural Resources:** Reduces dependence on the extraction of sand, gravel, and clay from land or sea quarries, preserving the landscape and terrestrial ecosystems.
- **Reduction of Waste and Disposal Costs:** By avoiding classification as waste (achieving End-of-Waste status), the high costs and environmental impact associated with transportation and landfill disposal are eliminated.
- **Infrastructural Sustainability:** Promotes the construction of port and coastal infrastructure more sustainably.

## CONCLUSIONS

**Task 4.5.3** of the RETURN Project has allowed the development of quantitative and probabilistic methodologies for multi-risk assessments, highlighting the complexity of the management of marine sediments and supporting the identification of effective and economically sustainable strategies for the mitigation of impacts deriving from the management of sediments subjected to dredging operations for maintenance or remediation.

The results have highlighted how the high costs of dredging, transport, and treatment represent the main challenges for the sustainability of interventions, which, combined with regulatory uncertainties and the complexity of authorization procedures can lead to extended timelines and create difficulties in the planning of operations. These are strongly influenced by the nature of the matrix to be treated, in fact, the high chemical-physical variability affects the remediation treatments, increasing their complexity and management. An additional phase to monitor is handling, in fact, during this operation, the risk of secondary contamination is high, therefore, the adoption of monitoring and prevention measures is required to avoid unwanted environmental impacts.

The risk analyses, SWOT, and FMEA have identified the main opportunities and criticalities of the project and quantified in detail the possible causes of failure and defined how to define the corrective actions necessary to mitigate their occurrence already in the design phase. The results of the risk analyses, together with those of the cost analysis, have facilitated the definition of optimized strategies and allowed a better allocation of resources based on the emerging priorities.

**Task 4.5.3** of the RETURN Project has highlighted how an integrated and multidisciplinary approach is of primary importance to address the criticalities and how it is fundamental to integrate the acquired knowledge with the optimization of processes for more efficient and sustainable management of sediments, in order to reduce environmental impacts and improve the economic sustainability of interventions.

The study conducted within **Task 4.5.3** has therefore allowed the development of work aimed at the analytical evaluation of the effects of handling and the treatment chain through the knowledge on treatment, on the rational management of treated sediments, and the integration of the acquired knowledge, which has led to a significant improvement in contaminated sediment management strategies.

Through the adoption of advanced analytical tools and an integrated approach to risk management, it has demonstrated how it is possible to address the process in a more efficient and sustainable manner, optimizing operations and minimizing environmental impacts.

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