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SUSTAINABLE MANAGEMENT OF SEDIMENTARY RESOURCES: A CASE STUDY OF THE EGADI PROJECT

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Abstract

Multiple activities carried out on coastal areas expose marine sediments to contamination and their management has a great socio-economic importance with a high impact on economic development of coastal areas. However, there is an increasing shift towards the use of more sustainable approaches for managing 'contaminated' sediments. Using a case study of the Favignana Habour in Italy, this paper evaluates three approaches for the management of these sediments. The results of simulations carried out by SiteWise™ software show that the use of contaminated sediment as filling material for Confined Disposal Facilities has lower environmental footprint than treatment and reuse of sedimentary resources on shore. The implications for these results for the development of effective policies and practices by all key stakeholders are discussed.

Key words: dredging, footprint, green and sustainable remediation, LCA, LCC, natural resource management, sediment, SiteWise™

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1. Introduction

A wide range of mechanical-biological processes Bortone and Palumbo (2007) define **sediments** as: *suspended or deposited solids, acting as a main component of a matrix, which has been, or is susceptible to being transported by water and they are an important natural resource for the economic development of many Countries*. Fig. 1 shows that effective sediment management plays a crucial role in the environmental, social and economic sectors, including habitat management, recreation and agriculture (Do-Hyung et al., 2013; Manap and Voulvoulis, 2015; Wen-Yen et al., 2016). From the social point of view, sediments form beaches which serve to reduce flooding, as well as to provide recreational spaces. From the economic point of view, especially in small islands, recreational spaces (e.g. for boating) are reduced as sedimentation can reduce the capability of coastal infrastructure to tie up boats (Ausili et al., 2012; Cappucci et al., 2011; Fernández-Fernández et al., 2019). From an environmental perspective, sediments play a vital role in maintaining the health and viability of aquatic ecosystems (Puente-Rodríguez et al., 2015).

Pollutants tend to be absorbed by particulate matter in aquatic environments, and to settle on the bottom, forming contaminated sediments (EPA, 2005). The accumulation of these contaminants can be due to natural or anthropogenic sources (Matache, 2018). Natural factors include all phenomena that exclude human impacts (e.g. volcanic eruptions, forest fires, and the natural processes performed by plants and animals).

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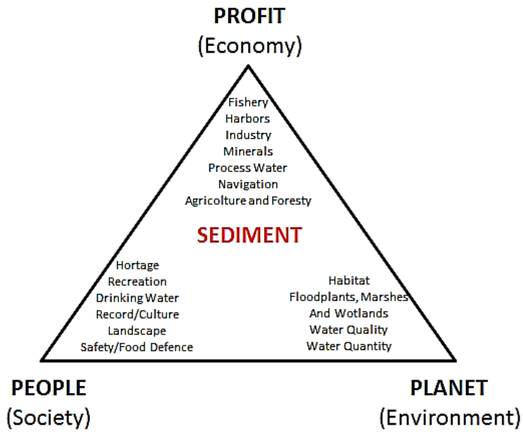

Fig. 1. The three fields of sustainable development and their interaction in relationship with sediment (Adapted upon Munasinghi (1998)

However, natural factors can lead to pollutant concentrations exceeding the threshold of contamination defined by national legislation (Aptiz et al., 2017; Cappucci et al., 2011). Anthropogenic sources, however, are represented by all the activities producing toxic or harmful substances and affecting the ecosystems (IMO, 2000). Anthropogenic contaminants may enter the aquatic environment through point sources, such as industrial or civil discharges, or from diffuse sources, such as runoff, erosion of farmland treated with pesticides and atmospheric deposition (Brettschneider et al., 2019; Moreira et al., 2019; Soliman et al., 2019). Apart from application on shore, few approaches have been outlined for remediation of contaminated sediments offshore (Apitz, 2008; Sparrevik et al., 2012). For this reasons, a conceptual model of contamination is the key part of seabed remediation process. Classification of sediments and management options are related to their level of toxicity and contamination. Usually three different colours, namely “green”, “yellow” and “red”, can be adopted to show whether dredged sediments can be effectively used for beach formation (Conti et al., 2009), disposed within Confined Disposal Facilities (CDFs) or landfilled (Cappucci et al., 2011).

While the legislation tends to mitigate the environmental impact derived from the movement of sediments in the coastal marine environment, there is much debate about prevention of the disposal of dredged material into marinas (Apitz et al., 2017). Hot spots of contamination are often the navigation channels, or internal parts of the harbors (Ausili et al., 2012).

Thus national and international legislations are rapidly evolving to take account of the rise of anthropogenic ‘contaminated’ materials in the sea, balanced against the concept of sediment as a "resource" and not as a "waste" (Junakova and Junak, 2017). The application of sustainability to reclamation known as sustainable remediation, together with the "green remediation", has been the object of recent studies (Anvar et al., 2018; Aptiz et al., 2017; Zijp et al., 2016). The SuRF groups, the Network for Industrially COntaminated Land in Europe (NICOLE), national bodies and agencies (USEPA and OSWER) were the main promoters of the development of these new concepts. The sustainable remediation is also the topic of ISO Standard 18504:2017 (ISO, 2017). However, environmental remediation within the contaminated sites generally focuses on restoring natural resources to an acceptable risk level for the society (Simion et al., 2011; Dauvin et al., 2018; Fernández-Fernández et al., 2019). In addition, remediation of contaminated hot spots may have negative impacts from local to global scales (Suèr et al., 2004). To support reclamation process, qualitative, semi-quantitative and quantitative tools are assessed and under development (Lemming et al., 2010). Thanks to these tools, it is possible to analyze a reclamation procedure by breaking it down into phases, analyzing environmental, economic and social impacts. After Volkwein et al. (1999), several authors compared several techniques and remediation options for specific contaminated sites including Life Cycle Assessment (LCA) (U.S.S.R.F., 2009; Wen-Yen et al., 2016). Since the green remediation program was launched by Environmental Protection Agency (EPA), various authors have started to evaluate and implement tools to apply sustainability criteria on remediation of contaminated sites. Remediation action can be performed in many different ways, depending on the level of contamination (EPA, 2005; U.S.S.R.F., 2009). The SuRFItaly Group (Sustainable Remediation Forum Italy; http://www.surfitaly.it/organization.html) has defined sustainable remediation "The process of management and remediation of a contaminated site, aimed at identifying the best solution that maximizes the benefits of its execution from an environmental, economic and social point of view, through a process decision-making shared with stakeholders". This definition introduced for the first time the concept of sustainability in the field of remediation that meets the needs of the present without compromising the ability of future generations to meet their needs (Brundtland, 1987).

Multi-Criteria Decision Analysis (MCDA) is an environmental management tool that can be adopted to choice suitable remediation technologies and for prioritization of intervention planning (Guerra et al., 2010; Linkov et al., 2006). Environmental assessment is however difficult to implement as the choice of technologies are often driven by profit and not by the desire to implement a sustainable process and or public services (Gebert et al., 2019). Addressing the social impacts is also often challenging because as many companies and authorities are often reluctant to increase the initial capital spend for intervention even if it could potentially become profitable in the long term. The first quantitative investigation of environmental assessment on a soil washing process for the remediation of a Pb-contaminated shooting range site was conducted by Kim et al. (2013), using a green and sustainable remediation tool (SiteWise^{TM}). Before this present study, the use of SiteWise™ has never been applied to dredging and remediation of contaminated sediment. In the present study, we used Favignana Harbor as a case study to assess the environmental impact of different options for sediment management.

2. Objectives

The aim of the present study is to test and provide a sustainable footprint of different options for sediment management. We provided support to local authorities aiming at more sustainable remediation by using SiteWise™ (Ferdos and Rosen, 2013; http://www.sustainableremediation.org). Our goal was to implement a management model of harbor sediments, which, after characterization (Ausili et al., 2012), may be reused avoiding landfilling (Cappucci et al., 2011).

In the present study, sediment management options from a small port layout located in Southern Italy have been used in order to: compare the footprint of different scenarios proposed by local authorities; and determine which has the lowest impact. The main objective was to evaluate which of the possible management options has the lowest impact. Based on the complexity of sediments management and the need to guarantee periodical dredging, as well as to sustain tourism in the area (by harbour, sportive activities and versus municipalities and tourist operators), a simple and straightforward analysis was implemented. A preliminary sediment characterization carried out before the new legislation criteria, suggested a low level of contamination that could compromise the use of sediment for beach replenishment (Ferrantini, 2012).

To avoid disposal into landfill, technical and economic analyses were carried out under the hypothesis that an average volume of 22,000 m^3 (estimated according to preliminary characterization carried out by local authorities; Ferrantini, 2012) must be periodically dredged and excavated to:

- create beach volleyball fields (to improve touristic services);
- restore the coast (by replenishment of the emerged beach and back shore);
- enlarge the port layout (with a CDF made with the dredged material).

In this context, the assessment of different scenarios was proposed by using the SiteWise™ software, providing individual alternatives, with relevant information related to the different options (i.e. GHG emissions; total energy used; water consumption; use of electricity; NOx emissions onsite; SOx emissions onsite; PM_{10} emissions onsite; total NOx emissions; total SOx emissions; total PM_{10} emissions).

3. Study area-Favignana Harbor

The Favignana Harbor (Fig. 2) is in the sheltered inlet of Cala Principal (north central area of Favignana Island), and is located in a Marine Protected Area. The harbour is equipped with a pier about 110 m long, which extends North-west. The smaller Molo S. Bernardo stretches for about 85 meters in a southerly direction. About 100 berths are available, 30 of which are dedicated to boats of travellers/navigators. On the seabed the Posidonia oceanica meadow is located (Marbà et al., 2014).

Frequent siltation of the structure is due to the anticlockwise circulation inside the harbor generated during mistral winds (Cappucci et al., 2017) and dredging activities must be carried out to guarantee navigation and safety (maintainance of navigation depth). Navigation is limited, especially close to the docks, due to sand transport under the effect of anticlockwise circulation that reduces the depth of the seabed. It needs periodic dredging of about 22.000 m^3.

4. Methodology and assumptions

Sediment characterization of the site was undertaken (Ferrantini, 2012) through a deterministic strategy. The characterization of superficial sediments allowed determination of the physical properties of the particles. The grain size revealed a percentage of silt and clay of about 1% and a D_{50} of approximately 0.215 mm. The analytical tests detected a moderate contamination (Ferrantini, 2012), exceeding the thresholds set by the Legislative Decree no. 152/2006, for Cadmium, Arsenic, Lead, Tin, PAH and TBT (Tributyl tin compounds used in anti-fouling paints). The outcomes from this preliminary study were used to identify the positioning of various sampling stations in areas where accumulation of pollutants takes place due to deposition of coastal sediments in front of Piazzale Marina.

Due to the contamination level, local authorities required technical support to assess the best option to manage the dredged material. Sediment must be removed to guarantee the navigation and we assumed that they should be isolated from direct contact with marine organisms and coastal water in case they are not treated to reduce concentration of contaminants. The main hypothesis is that after the characterization, the entire volume of sediment will be managed according to the following three scenarios (Table 1):

1. Sport, to build beach volleyball fields;
2. Coast, to replenish the coasts;
3. Harbor, to fill CDF.

The study of the different sustainability assessment was carried out by using SiteWise™ (Bhargava and Sirabian (Battelle), 2013).

A detailed technical and economic analysis of treatment and remediation technologies was conducted (i.e. (GHGs), use of energy, electricity from renewable and non-renewable sources, criteria on air pollutants (NOx, SOx, PM), use of water, consumption of resources (soil consumed), and safety of worker (risk of accidents, lost hours)), on the basis of literature review, budget estimation (market research) and results of tests carried out on other contaminated sites (Ferrantini, 2012).

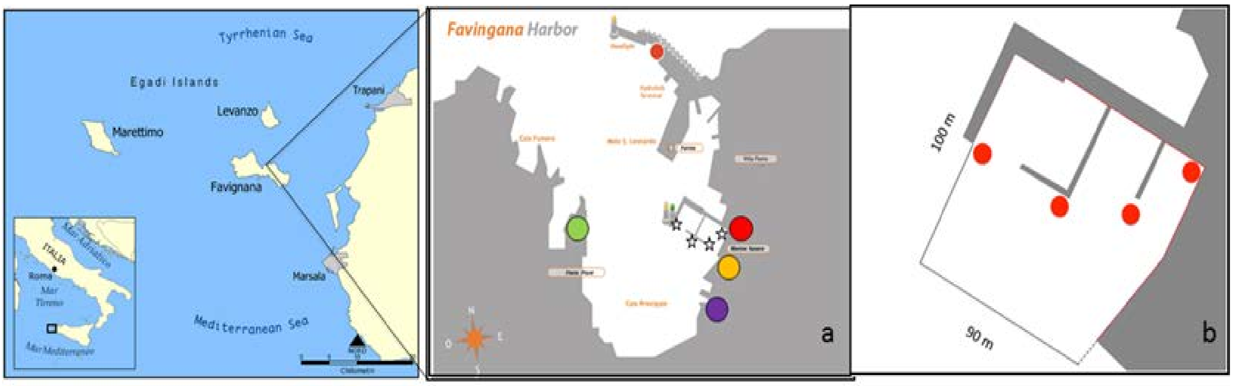

Fig. 2. Egadi archipelago and Favignana Harbor. (a) Florio's factory (green); Gas station (red); Wastewater discharge (purple); Boat repair (orange). (b) Red dots indicate sampling station for characterization of seabed

Table 1. Scenarios for sediment management and their phases

Scenario	*Volume to be dredged*	*Volume to be treated*	*Phases*
N	m^3	m^3	
1 sport	22,000	22,000	Characterization → Dredging → Transport → Storage → Treatment → Installation of the fields
2 beach	22,000	22,000	Characterization → Dredging → Transport → Storage → Treatment → Requalification of coastal area
3 harbor	22,000	0	Characterization → Dredging → Harbor infrastructure

The most reliable sources of data and information have been catalogued, classified and, for each technology, a range of costs was determined.

4.1. Technical analysis of remediation technologies

Due to the low level of contamination of the Marine Protected Area and the limited extension of the Harbor layout (i.e., volume to be excavated), dredged sediment could be subject to:

- treatment before their reuse on coastal areas (beach nourishment);
- treatment and reuse on-shore (in order to ignore the bioavailability and effects of contamination on marine organisms as material will not be in contact with coastal marine water bodies);
- direct disposal within confined disposal facilities (isolated from marine organisms and water).

The total footprint is calculated by integration of all the activities. The data required to model each stage of remediation scenarios in Table 2 were different, but the following inputs are mandatory to run SiteWise™ simulations:

- material required for each stage of remediation;
- transportation of both personnel and material (machinery, etc.);
- all activities to be performed off shore and on shore (including mobilization and de-mobilization of devices);
- management of sediment produced by dredging and disposal on-off-shore.

4.2. SiteWise™ simulation for different management option

The evaluation of each intervention alternative is performed by breaking it down into individual blocks that can represent the individual phases of the alternative (or their combination/aggregation). The dredging process, for example, consists of separated blocks/phases: study and design, dredging, equipment transport, personnel transport. The environmental footprint is calculated for each block, and these footprints are then combined to provide the output related to the whole alternative. In this way it is possible to determine which alternative produces the highest environmental footprint, or how to reduce it by using energy from renewable sources. In order to insert the inputs in the easiest way and reconstruct the modules and the phases that make up the alternatives in the program, the following subdivision was used (Fig. 3):

- component 1 = characterization and dredging;
- component 2 = transport (to the treatment facility or to the CFD);
- component 3 = treatment;
- component 4 = final destination of sediments.

The electrical production of California State was selected as it is the most similar to percentage of renewable electricity (26 vs 24 %), CO_2 emissions per MWh (800 vs 680 pounds/MWh) and electricity production efficiency (0.426 vs 0.445 gross electricity yield per unit of fuel energy content) compare to the study area. In Scenarios 1 and 2, pretreatment (storing and drying) of $22x10^3$ m^3 ($59x10^6$ kg) of sediments with the use of earth-moving machines was considered. Then, a soil washing treatment plant with a potentiality of $5x10^4$kg/h was considered. Unit conversion and assumptions used for environmental footprint analysis are respectively reported in Table 3 and Table 4.

4.3. Economic specification and assumption of management scenarios

The costs of the three different scenarios were estimated based on the approach of Bortone and Palumbo (2007), executive projects and through quotations to companies.

The cost analyses took account of identical activities to be carried out for each different scenario, including: characterization, dredging, transport, storage and treatment. A second group of costs were then considered in relation to specific activities to be carried out for the following three different scenarios:

- installation of beach volleyball field (for sediment reuse within a beach volleyball field);
- requalification of coastal area (for sediment management to be reused along the coast);
- construction of CDFs (to enlarge the port layout).

Cost for taxes and safety were considered and included within each different scenario.

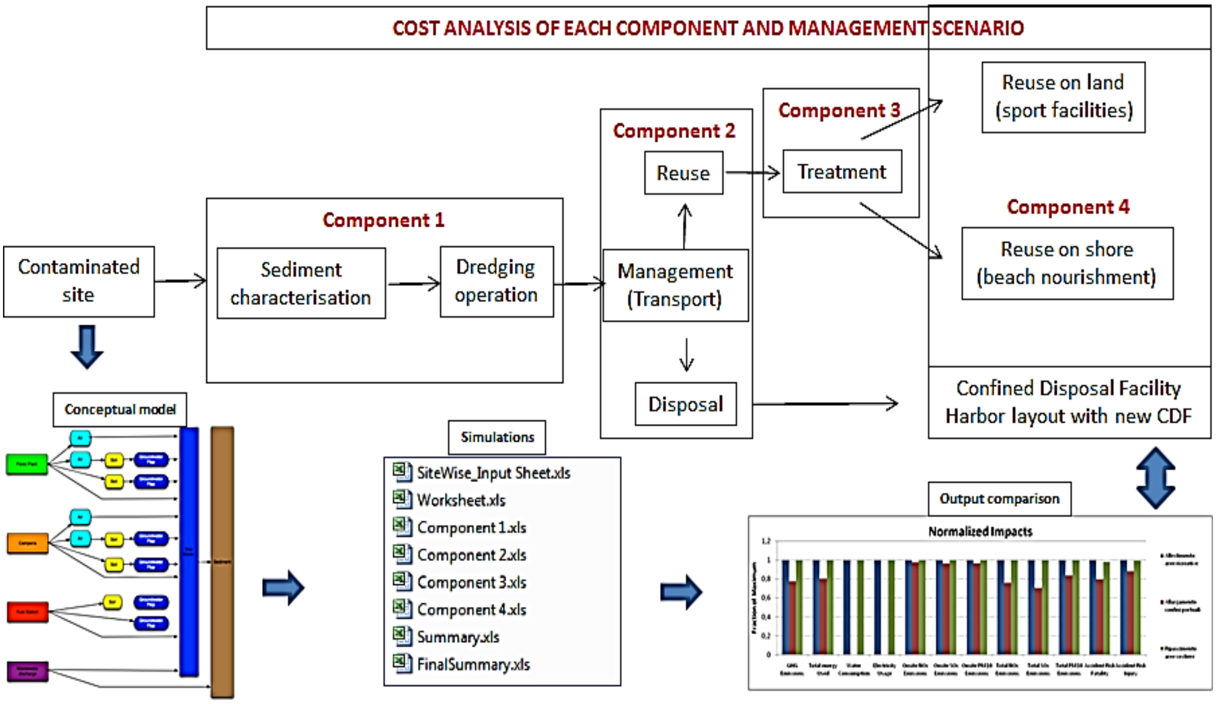

Fig. 3. Flow diagram of the simulated scenarios (conceptual model by Ferrantini, 2012)

Table 3. Conversion from Site Wise^{TM} units to international system

Value	***Conversion units** (from/to)*
3,412	BTU/kWh
947.867	BTU/Mj
0.001	Mj/BTU
1.055	kJj/BTU
0.746	kW/hp
33,013	ft lbs/min hp
2.204	lb/kg
0.454	kg/lb
2,204.6	lb/metric ton
1,000	kg/metric ton
3.785	L/gal
8.34	lbs H_2SO/gal

Table 4. Technical specifications and assumptions adopted for each scenario

COMPONENT 1 - Characterization and dredging				
Transport for "characterization"	Number/quantity	Distance [km]	Round trip	Vehicle
Personnel for study area	2	22	6	diesel car
Personnel for study area	1	500	2	airplane
Personnel for sampling	2	22	2	auto diesel

Sediment samples	4	500	1	airplane/ferry
Transport for "dredging"	Number/quantity	Distance [km]	Round trip	Vehicle
Personnel for dredging operation	4	3	12	diesel car
Dredge	1	100	2	ferry
Silt curtains	1480 kg	100	1	ferry
COMPONENT 2 - Transport of sediment				
Transport of dredged sediment	Number/quantity	Distance [km]	Round trip	Vehicle
Port - treatment volume	22,000 m^3	3.6	1,100	truck 20 m^3
treatment area – port	0 m^3	3.6	1,100	truck 20 m^3
treatment area - destination area	21,350 m^3	4	1,070	truck 20 m^3
Waste from treatment area – port	650 m^3	3.6+22	35	truck 20 m^3 + ferry
Truck drivers	2	3	368	diesel car
COMPONENT 3 - Treatment - soil washing				
Transport of personnel	Number/quantity	Distance [km]	Round trip	Vehicle
Personnel for treatment facilities	2	3	590	diesel car
Personnel for moving soil	2	3	590	diesel car
Personnel for installation	4	3	40	diesel car
Personnel for CLS transport by trucks	2	3	12	diesel car
Facilities	Number/quantity	Distance [km]	Round Trip	Vehicle
Facilities for moving soil	1	3	2	Truck
Pumps for soil washing	2	100	2	ferry + trucks
Hydrociclons	2	100	2	ferry + trucks
Conveyor belts	1	100	2	ferry + trucks
Water treatment	1	100	2	ferry + trucks
Pre- treatment (sifts)	1	100	2	ferry + trucks
Dehydration of treated sediments	1	100	2	ferry + trucks
Pumps for hydrociclons	2	100	2	ferry + trucks
Materials	Number/quantity	Distance [km]	Round Trip	Vehicle
Concrete - treatment area	300 m^3	22+3	30	truck 20 m^3
Concrete - storage area	960 m^3	22+3	96	truck 20 m^3
Concrete - treatment area	0	22+3	30	truck 20 m^3
Concrete - storage area	0	22+3	96	truck 20 m^3
PVC for prefabricated - treatment area	4,000 kg	100	1	ferry + trucks
PVC for roof - storage area	7,000 kg	100	1	ferry + trucks
Steel for covering PVC support	2,500 kg	100	1	ferry + trucks
Materials for treatment	Number/quantity	Distance [km]	Round Trip	Vehicle
Water	0.1 m^3/t soil	\	\	Pumps
ETAC (ethyl acetate)	0.18 kg/t soil	100	1	Ferry + trucks
COMPONENT 4 - Recreational area facilities (4400 m^2)				
Playground' s construction	Number/quantity	Distance [km]	Round trip	Vehicle
Personnel staff area	4	3	40	diesel car
Sediment	2,200 m^3	\	\	\
TNT fabric	440 kg	100	1	ferry
PVC for enclosed spaces	4,000 kg	100	1	ferry
Protection networks	81 kg	100	1	ferry
Lighting system (steel)	174 kg	100	1	ferry
COMPONENT 4 – Beach nourishment				
Sediment movement	Number/quantity	Distance [km]	Round Trip	Vehicle
Vehicle to be used for land	19,225 m^3	3	1	truck
Personnel for moving sediment	2	3	53	diesel car
COMPONENT 4 – Harbor				
Dredging and CDF	Number/quantity	Distance [km]	Round Trip	Vehicle
Dredger	22,000	100	2	crawler crane (25t)
Personnel staff area	4	3	64	diesel car
General concrete	14,790,000 kg	22	1	ferry+ trucks
Steel	102,000 kg	22	1	ferry+ trucks
Scow tenders	2	0.5	32	zodiac

5. Results

5.1. Environmental footprint of the three scenarios

Results for each alternative are provided in Table 6 where data refer to m^3 of dredged sediment. The enlargement of Harbor layout facilitates the deposition of contaminated sediment over a confined facility that is isolated from the marine habitat. As a consequence, there is no consumption of electricity and water, and GHG and other emissions are lower compared to other options (total NOx emissions -25%; total SOx emissions -30%; total PM_{10} emissions -15%). The total energy used for recreational areas is much higher (263.743 kWh) compared to other solutions (+20%) (Table 2). In Fig. 4 an example of SiteWise™ outputs is reported to show the GHG emissions, the total energy used and the water consumption of each component for the scenario 1 (recreational area for sport activities). The highest impact component is "sediment characterization and dredging" (C1). Also the "treatment" component (C3), has a relevant footprint. On the other hand, the "transport" and "sediment repositioning" components require less resources. Component C2 (Transport of sediment) has a lower footprint, and the impact of the components "transport" and "treatment" are null. The alternatives "recreational areas" and "coastal restoration" lead to similar impacts (e.g. GHG emissions of 11.632 kg/m^3 and 11.623 kg/m^3 respectively). While those relating to the "port layout" alternative are significantly lower (e.g. GHG emissions of 90.42 kg/m^3).

GHGs emission is higher during the "treatment" than "transport" and "sediment repositioning" (transport / C3) to the storage area (which respectively are equal to total amount of 46.000 kg and 21.000 kg and are almost irrelevant (Fig. 4 top). Different values were obtained for PM_{10} emission: characterization and dredging (C1) is significantly higher (1.230 kg) than minor contribution of transport (1.8 kg), treatment (277.3 kg) and sediment repositioning (10.9 kg).

The total amount of onsite PM_{10} emission is lower in case of direct placement of dredged sediment into a CDF, while an increase of about 3% is observed with other scenarios.

5.2. Economic analysis of remediation technologies

According to the preliminary analysis by Ferrantini (2012), which showed the costs for different treatment processes, in this study we adopted soil washing as the most convenient and effective solution. The alternatives have an economic impact that is influenced by the processing chain for clean-up operation and installation of the destination area. Such differences in the management option produce differences in the estimated expenditure (Table 7). The alternative "Preparation of recreational areas" has a higher cost ($ 1,566,745, i.e. € 1,368,500) due to the work for the preparation of the beach volleyball fields (the estimated cost is around € 200,000). The cost of preparation increases the intervention cost of "Coastal areas restoration", as "Preparation of recreational areas" (the preparation of the beach volleyball fields) have to be added. Table 8 summarizes the impact of each scenario on the environment. It can be seen that the Harbor scenario is the only one having low impact in terms of water use and electricity consumption. More detailed information of environmental impacts of the studied scenarios is provided by Fig. 5, where the impacts are normalized. All metrics are normalised (the alternative with the highest impact is assigned a value of 1.0 and impacts for the other alternative metrics are presented as ratios to that unit). The alternatives "Sport Area" and "Coastal restoration" are very similar.

6. Discussions

Dredging within Favignana's Harbor is periodically needed to ensure the safety of navigation and an adequate depth of the sea floor. This study evaluated three possible types of interventions on the territory: Sports facilities; Coastal restoration; Harbor, as the large part of dredged material is slightly contaminated. In this study, SiteWise™ (v3) was used to evaluate a dredging project not only to determine the impact of different stages of the remediation, but also to understand which management options has the lower environmental footprint.

Table 6. Comparison among the scenarios (data refer to m^3 of sediment)

Scenario	***GHG emission***	***Total energy used***	***Water consumption***	***Electricity used***	***Onsite NOx emission***
	metric kg/m^3	kWh/m^3	m^3/m^3	kWh/m^3	metric kg/m^3
recreational areas	116x10^2	346.35	294x10^{-2}	1.38	105
port layout	90x10^2	279.75	0	0	103
coastal restoration	116x10^2	346.35	294x10^{-2}	1.38	105
Scenario	***Onsite SOx emissions***	***Onsite PM_{10} emissions***	***Total NOx emissions***	***Total SOx emissions***	***Total PM_{10} emissions***
	metric kg/m^3	metric kg/m^3	metric, kg/m^3	metric, kg/ m^3	metric, kg/m^3
recreational areas	160x10^{-1}	516x10^{-2}	148	27	7x10^{-2}
port layout	150x10^{-1}	516x10^{-2}	113	19	6x10^{-2}
coastal restoration	160x10^{-1}	499x10^{-2}	149	27	7x10^{-2}

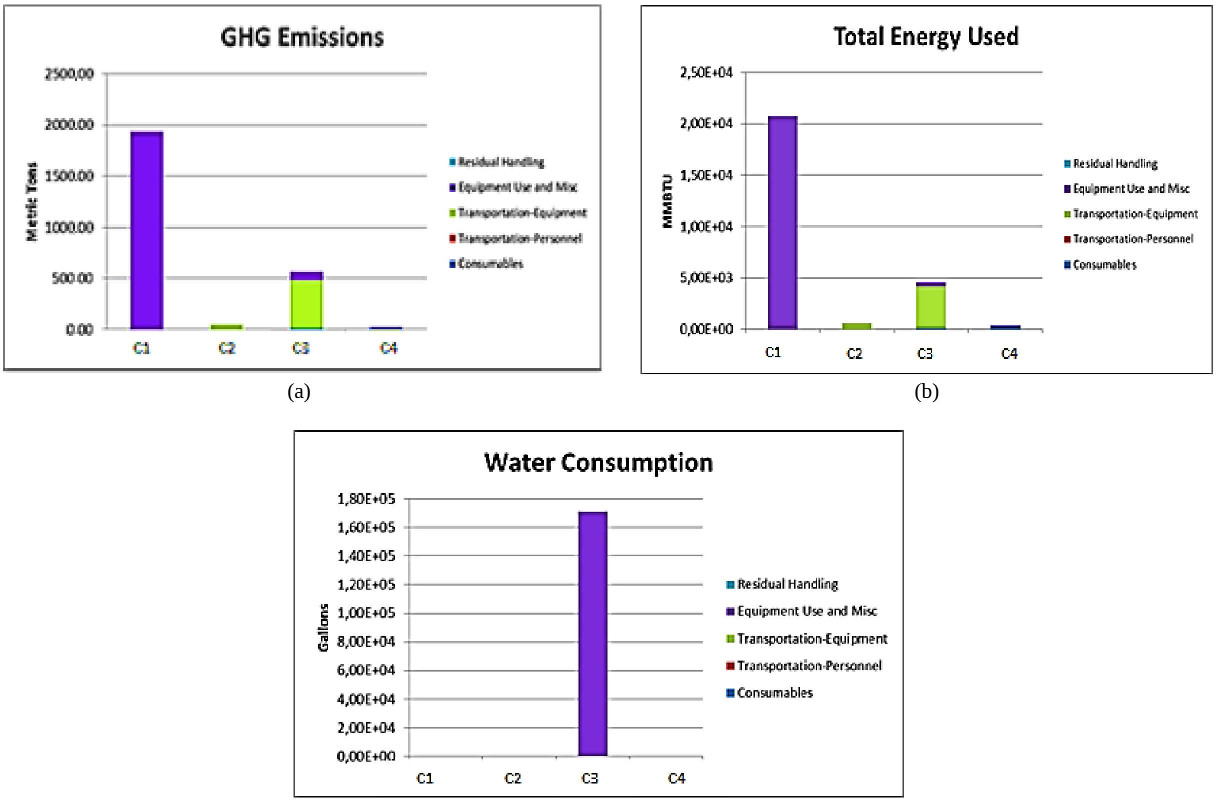

Fig. 4. Example results of Scenario 1 (recreational area for sport activities) produced by SiteWise™. GHG emissions, total energy consumption and water consumption are plotted for each component (C1: Sediment characterisation and dredging operation; C2: Transport; C3: Treatment; C4: Coastal intervention) with US$ Unit

Table 7. Results of the economic evaluation

Scenario	***Stages of remediation and reuse of sediment***	***Cost***	***Total cost***
N	€	€	€ ($)
1 **Sport**	Sed. Characterization: Sed. Analysis: Sed. Dredging (6.7 €/m^3) : Sed. Transport: Sed. Treatment: Installation of beach volley:	25,000 6,000 148,000 13,500 994,000 200,000	1,368,500 (1,566,745)
2 **Coast**	Sed. Characterization: Sed. Analysis: Sed. Dredging (6.7 €/m^3) : Sed. Transport: Sed. Treatment: Requalification of coastal area:	25,000 6,000 148,000 13,500 994,000 16,000	1,211,000 (1,368,000)
3 **Harbor**	Sed. Characterization: Sed. Analysis: Sed. Dredging (6.7 €/m^3): Sed. Transport: Sed. Treatment: Infrastructure (new harbor layout):	25,000 6,000 148,000 0 0 900,000	1,079,000 (1,218.89)

The present study confirms the findings of Kim et al. (2013) related to the relevant contribution of soil washing treatment compare to the other stages of remediation projects. The consumable chemicals, electric energy consumption for system operation, and equipment use are the major sources of environmental pollution to occur during the soil washing process. The results of our study demonstrated that the footprint of a Confined Disposal Facility (CDF) option is lower because the reuse of dredged contaminated sediment on coastal marine environment certainly need a lower concentration of contaminants and ecotoxicology level compare to dredged material that can be spilled over a completely isolated coastal infrastructure. The total energy used for recreational areas is much higher compared to other solutions (+20%), because the installation of beach volleyball facilities requires additional materials and components (Table 2).

Table 8. Impact categories Table of normalized impact. The outputs reported with red (high), yellow (medium) and green colour (low) are based on a 30% difference (if the two data points are within the 30% difference then both the alternatives are assigned the same high, medium, or low index)

Scenario	***GHG Emissions***	***Energy Usage***	***Water Usage***	***Electricity Usage***	***Onsite NOx Emissions***
Sport	High	High	High	High	High
Coast	High	High	High	High	High
Harbor	High	High	Low	Low	High
Scenario	***Onsite SOx Emissions***	***Onsite PM10 Emissions***	***Total NOx emissions***	***Total SOx Emissions***	***Total PM10 Emissions***
Sport	High	High	High	High	High
Coast	High	High	High	High	High
Harbor	High	High	High	High	High

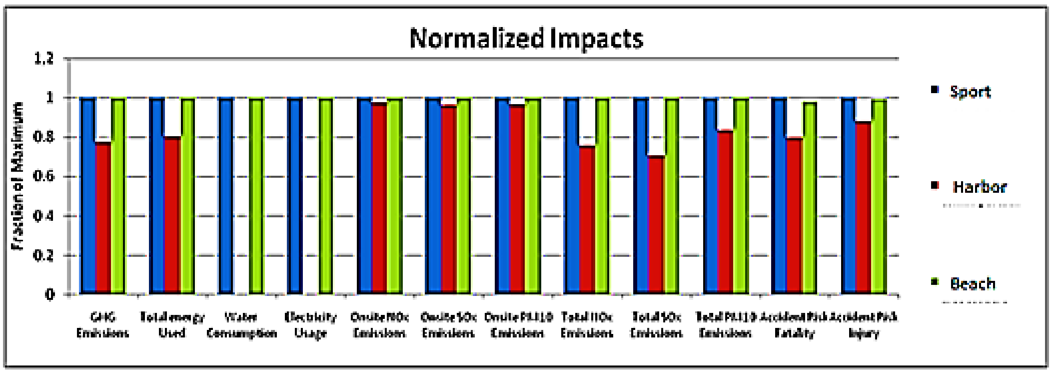

Fig. 5. Normalized impact category diagram generated in the Final Summary Sheet of Site Wise for each scenario

The highest impact component was "sediment characterization and dredging" (C1), as it involves the use of specific equipment with high power and high consumption. Also the "treatment" component (C3), has a relevant footprint as it consumes a lot of water. On the other hand, the "transport" and "sediment repositioning" components require less resources. Component C2 (Transport of sediment) has a lower footprint because the distances to be covered on the small island is reduced and the equipment uses technologies with lower impacts compared to the other components. The impact of the components "transport" and "treatment" are null due to the enlargement of the Harbor layout and direct discharge of sediment from the dredger into the CDF. The alternatives "recreational areas" and "coastal restoration" led to similar impacts, while those relating to the "port layout" alternative were significantly lower.

As shown in Table 8 and Fig. 5, the alternatives "Sport Area" and "Coastal restoration" are very similar because the components "characterization and dredging" and "treatment" are mandatory for those scenarios and the transport component is not considerably different as the island is small and, as a consequence, distances are very limited. Moreover, the "storage” component (within a temporary sediment deposit) has a lower impact compare to "characterization and dredging" and "treatment" component. The lowest impact is generated by the enlargement of Harbor layout scenario. In fact, the two components of "transport" and "treatment" are avoided with this option. However, it has some impact during the immediate intervention, as the use of reclaimed tanks into which contaminated sediment is located, does not allow omitting future monitoring and intervention. Moreover, in that scenario the sediments are considered as waste and not as a resource, like in the other two alternatives.

A CDF (Confined Disposal Facility) was the cheapest option and presents lower water and energy consumption. Beach replenishment along the coast is the beneficial use that most authorities should follow. The on-shore recreational activities (like beach volleyball fields) is an innovative promising option, indicated for reduced dredged volume of sediment because it favour the reuse and increases the amount of goods and tourism services. However, the possibility to realize beach replenishment will be strongly influenced by the eco-toxicology of dredged sediment and the presence of the *Posidonia oceanica* meadow in shallow water (close to the shore line and within the active zone of the submerged beach).

From the economic point of view, the parameters that influence the operations of the considered process have a direct influence also on the respective costs. Those parameters are: volume of sediments to be dredged, seagrass meadow, and extension of the storage area to be waterproofed. It is important to observe how the scenario that involves the construction of a CDF within the Favignana Harbor as well as lower consumptions of water and electricity (generated by the lack of treatment) also generates lower emissions of GHGs in the atmosphere. Global climate change is actually one of the major environmental issues of the present and the future (GEO-5, 2012). Evidence for global climate change is increasing and there is a growing consensus that the most important cause is humankind's interference in the natural cycle of GHGs (Crutzen and Stoermer, 2000; 2013). This study confirms that human activities enhance and influence the emission of natural greenhouse effect by adding other GHGs such as carbon dioxide and nitrous oxide to the atmosphere (Pallottini and Cappucci, 2009; Pascucci et al., 2008; Stoddart et al., 2019).

Even if green and sustainable terms are sometimes interchanged, green remediation can be associated to environmental components, while sustainable remediation can be associated with environmental factors, social responsibility and economic aspects. In fact, these two notions can be connected as Green and Sustainable Remediation (GSR), addressing a broad range of environmental, social and economic impacts during all remediation phases (Reddy and Adams, 2010). The results obtained in our study revealed that enlargement of the port layout is the more cost and time effective option even if sediments (as un-renewable natural resources), are taken out of the coastal system and used to fill the new infrastructure.

Furthermore, from a regulatory point of view, there are still no laws to manage in a quantitative way the application of the sustainability concept and apply it to practical cases. In addition, the complexity of the sediment regulations for water and waste management, increase the complex application of sustainability criteria to the sediment management options.

7. Conclusions

Dredging of sediment with low contamination levels harbors is often required to facilitate recreation and beach formation. However, the sustainability of land reclamation is a major challenge and presents many obstacles, including lack of economic incentives, use of lower impact technologies and limitations in acceptance of new technologies by companies. In addition, technical restrictions must be resolved (i.e. data input should be defined and standardized at national and international level). The methodological approaches and evaluations as well as the ongoing research of technologies need to deliver quantitative analysis and must be carried out considering a conjoint protocol. At the same time, the high costs of low impact technologies lead to the choice of traditional and established equipment and know-how, such as, in the case of excavation sediments, removal and disposal

Reuse of sediment often meets the waste status of dredged sediments. When a sustainable approach could lead to regeneration and reuse of material in various sectors, the legislation does not always support a sustainable approach to managing the sediments. Waste regulations often hamper reuse projects with environmental constraints which were not designed for sediments reuse. They are often country specific and make EU-wide projects difficult. However, reuse can provide environmentally beneficial options for site restoration, for fresh (river) and coastal (marine) water good status as indicated by the Water Frame Directive 60/2000 and for climate change mitigation. The Italian legislation is continuously evolving, but still does not consider risk analysis as a decision tool for dredging the contaminated sediment. Italian national legislation recently set out the criteria for the classification of sediments and their possible reuse or disposal offering a more comprehensive regulatory framework for contaminated sites. However, areas outside of the contaminated sites of national interest still require specific attention.

The use of SiteWise^{TM} seems a promising tool in applied sedimentology and coastal engineering even if the suggested alternative scenarios are not necessarily always accepted or welcomed by local authorities and stakeholders. Stakeholder could adopt the results to manage the dredged sediment in other sites considering different options and related environmental footprint (e.g. consumption of natural resources and energy, and emissions into atmosphere).

Results of the present study are useful for the decision-making phase and for the competent authorities, but also decisive for the scientific community as they integrate results of conventional techno-economical assessment studies. Specific attention should be placed on implementing low energy demand technologies, particularly if electricity mix relies on fossil fuel and this scenario may impact the footprint of sediment management options.

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