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SEDIMENTS AS A DYNAMIC NATURAL RESOURCE - FROM CATCHMENT TO OPEN SEA

# Sustainable sediment management in coastal infrastructures through an innovative technology: preliminary results of the MARINAPLAN PLUS LIFE project

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**Abstract**

Purpose: The paper aims to show the preliminary monitoring and field test results of the innovative technology tested in the framework of the MARINAPLAN PLUS LIFE project for sustainable management of sediment in harbour areas. The technology is based on a patented jet-pump able to keep the seabed at a certain level over the time through a continuous removal of silting sediments.

Materials and methods: Preliminary field tests were performed to optimise the design of the demo plant and a monitoring plan was devised to evaluate the technical, economic and environmental impacts of the technology, in particular in comparison with dredging.

Results and discussion: The preliminary tests showed promising results in terms of efficacy and efficiency of the sediment by-passing device. At the maximum sediment removal capacity, the ejector tested in Cervia showed a sediment flow rate of about 2 $m^3h^{-1}$, with an electric consumption of about 3.5 kW, and an influence diameter of about 5-7 m, after 15 days of working operation. On the basis of the preliminary results, a 10 ejectors demonstrator plant has been designed and realized, and it is now in operation. The analysis of sediment and marine flora and fauna in the installation area in comparison with control areas indicates the negative impact of cyclic dredging in the harbour inlet area.

Conclusions: The innovative technology promoted by the MARINAPLAN PLUS LIFE project is a promising solution to manage sediment siltation in harbour areas through a cost-effective and low environmental impact technology. The monitoring of the demo plant operation is fundamental to fully validate the technology and to demonstrate its efficacy and sustainability.

**Keywords** Environmental impact • Harbour areas • Macrobenthic fauna • Sediment by-passing system • Sediment management

## 1 Introduction

The water field around ports is an area where intense sediment transport rates usually occur, and is affected by low water velocities especially close to the entrance and inside the port basin. Consequently, sediment is retained and accumulated in these areas, creating problems to navigation. The result is that harbour basins and approaches are frequently silted and require ordinary dredging maintenance. The dredging process involves the removal of sediment in its natural deposited condition by using either mechanical or hydraulic equipment. Dredging is a consolidated and proven technology (Bray et al. 1996), but involves considerable drawbacks, such are the environmental impact on marine flora and fauna (Ohimain et al. 2004; Ponti et al. 2009; Suedel et al. 2012; Manap and Voulvoulis 2015; Ragnarsson et al. 2015), the increasing of turbidity (Cutroneo et al. 2013), the mobility and diffusion of contaminants and pollutants already present on the seabed (Torres et al. 2009; Schaanning et al. 2011), the obstruction of navigation and the relatively high yet low predictable costs. Moreover, the management of sediments once dredged, faces technical, economic and legislative obstacles, which are particularly relevant in the case of small-medium marinas, especially if the sediments are contaminated (Mali et al. 2017). Moving towards sustainable sediment management in harbour areas requires the adoption of innovative technology able to reduce the environmental impacts and to minimise and standardize costs.

The MARINAPLAN PLUS LIFE project started in October 2016 and foresees the construction of a sediment by-passing plant in the harbour channel inlet of Cervia (Italy), which is located in the Adriatic Sea and can be considered as a representative siltation case study for Middle-North Adriatic Sea harbours and marinas. Trevi SpA is the project coordinator, whereas Cervia Municipality, the University of Bologna and ICOMIA are project partners. The core of a sediment by-passing plant is the jet pump. The jet pump is a well-known and reliable technology which has several applications in different fields (Stewart 2019). In a sediment by-passing plant, the jet pump is placed on the seabed and transfers momentum from a high speed primary water jet flow to a secondary flow that is a mixture of water and of the surrounding sediment. The sediment-water mixture is then conveyed through a pipeline and discharged in an area where the sediment can be picked up again from the main seawater current or where it is not an obstacle for navigation. The technology is reliable since it has been applied starting from the '70s for coastal application (McNair 1976), it requires limited personnel, is extremely portable and can be assembled at reasonable cost. The sediment by-passing technology tested within the MARINAPLAN PLUS LIFE project has two important novelties: the first is that the main element of the plant, called "*ejector*" (Fig. 1), is an open jet pump (i.e. without closed suction chamber and mixing throat) with a converging section instead of a diffuser and a series of nozzles positioned circularly around the ejector. The technology has been under development since 2001 and has already been applied in two experimental plants in Italy (Amati and Saccani 2005; Bianchini et al. 2014): the ejector works on a limited circular area created by the pressurized water outgoing from the central and circular nozzles, whose diameter depends on the sediment characteristics such as, for example, the repose angle. By ejector integration in series and in parallel it is possible to create or to maintain a seaway.

The second main novelty of the MARINAPLAN PLUS LIFE project application is that the sediment by-passing plant has been designed and is controlled to by-pass the silting sediments, and not to remove them from the seabed. This feature is important in authorisation and permit procedures, since the mass balance in the area wherein the ejectors are installed can be considered as zero, and so the plant operation should not be equated to dredging accordingly to the Italian Law Decree 173/2016.

The paper shows the preliminary results of the MARINAPLAN PLUS LIFE project. In particular, the paper focuses on the difficulties that the project development faced in the design phase of the demo plant, including the permit and authorisation process. The paper includes the analysis of the preliminary field tests carried out in July 2017, the description of the monitoring plan and the first environmental monitoring actions carried out. This information is of paramount importance to fully validate the technology and to demonstrate its efficacy and sustainability both in economic and environmental terms.

## 2 Materials and methods

### 2.1 Site description

Cervia is a municipality counting about 30,000 inhabitants. Nevertheless, as normal on the Emilia-Romagna region coast, Cervia is characterised by a dramatic increase in population during the summer holiday season. The Marina of Cervia is located on the North-East side of the old harbour (Fig. 2), reserved for recreational craft, consisting of a dock with eight piers. The Marina has a capacity of 300 boats with a maximum length of 22 m. Cervia harbour is affected by a cyclic problem of inlet silting. The technological solutions adopted until now, including seasonal dredging and/or sand underwater re-suspension by boat propellers, as well as docks lengthening (completed in 2009), have not solved the siltation problem: as highlighted by Table 1, from 2009 to 2015 the Municipality invested about 1.3 million Euro in dredging and sediment handling with propellers (i.e. a mean yearly cost of 185,000 Euro).

Natural sand transport is present alongside the coast line, moving from North to South, as confirmed by regional studies (ARPAE 2016). Nevertheless, a more in-depth analysis was needed to properly design the demo plant: in particular, the ejector placement is defined to prevent sediment siltation in the most critical area, while the ejector number is evaluated based on the estimated sediment quality/composition and quantity to be removed from that area. The most critical area for sediment siltation and the estimation of sediment quantity to be removed can both be identified through bathymetries analysis. The siltation phenomena in Cervia harbour is monitored by the Municipality through seasonal bathymetries. Since 2009 (after dock lengthening) bathymetries have been carried out through a digital hydrographic ultrasound system with narrow emission cone, preliminary calibration and differential GPS Trimble positioning system; the resulting error is estimated as not exceeding 3 cm. So, the siltation phenomena at the harbour inlet can be evaluated on a robust historical database.

**2.2 Monitoring plan**

Literature data already demonstrated that a sand by-passing plant can be more economical than dredging (Bruun 1996; Boswood and Murray 2001; Dean and Dalrymple 2004; Bianchini et al. 2019), even if operation and maintenance costs are usually based on estimation more than on real data. One of the objectives of the MARINAPLAN PLUS LIFE project is to measure the operation and maintenance costs over a period of at least 12 months. The efficacy of the demo plant will be monitored through bathymetries in the ejector area, while the efficiency of the demo plant will be assessed through power consumption.

The environmental impacts caused by technologies involved in sediment handling are related to effects on the surrounding marine environment. Environmental monitoring activities are fundamental in the MARINAPLAN PLUS LIFE project, since reliable data are crucial i) to evaluate the impact of the demo plant on the marine environment, ii) to compare the impact of the demo plant with that of dredging activities, and iii) to design sustainable sediment management. The environmental impact of sand by-passing systems has never been analysed in detail (Bianchini et al. 2019). Therefore, another interesting novelty of the MARINAPLAN PLUS LIFE project is the assessment of the demo plant impacts on marine benthic and fish communities, due to both sediment reworking and possible noise production.

Possible impacts of the demo plant on sediment characteristics, benthic macroinvertebrates and fish assemblages need to be assessed simultaneously at a variety of spatial scales, encompassing the full extent of the environmental variability of the area where the ejectors are positioned. Sampling sites are located in one putatively impacted location in front of the port of Cervia (location I; 44º 16.162’ N, 12º 21.667’ E) and in four control locations, placed 600 m (location N1; 44º 16.484’ N, 12º 21.512’ E) and 1200 m (location N2; 44º 16.718’ N, 12º 21.390’ E) north and 600 m (location S1; 44º 15.857’ N, 12º 21.822’ E) and 1200 m (location S2; 44º 15.573’ N, 12º 21.976’ E) south of the impact location respectively (Fig. 3). Two sampling areas (about 800 $m^2$ each) are defined within every location, 20-30 m apart. The two areas within the putatively impacted location are represented by the sediment removing and discharging areas, i.e. the ejectors and ejector discharge areas. In May 2018, i.e. one year before demo plant operation and a few weeks after a dredging operation at the harbour inlet, four replicated samples of marine sediment and fauna were manually taken at each sampling area by scientific SCUBA divers, using an aluminium frame (23.5×13.5 cm). Laboratory analyses encompassed sediment grain size (percentage of mud (<63 µm), fine sand (63-250 µm) and medium sand (> 250 µm) fractions), percentage of organic matter, dry weight of shell debris and benthic macrofauna determination to the lowest possible taxonomic level (after sieving on 0.5 mm mesh sieve). Fish assemblages were sampled by GoPro Hero 5 video cameras randomly placed within each study area. High definition (Full-HD) 30 minutes digital videos were recorded for each video camera deployment. Each video was further split into four sections long seven to eight minutes, further considered as replicates.

For each replicate of benthic samples, indices of macrofaunal assemblage diversity, namely species richness (*S*), total abundance (*N*), Hill's species diversity index (*N1*; N1 = Exp H', where H' is the Shannon index based on natural logarithm) and Hill's evenness index (*N10*; N10 = N1/S), were calculated. Hill's diversity index gives the number of species that would have been found in the sample if all the species had been equally abundant (Hill 1973). Evenness indicates the distribution of the individuals among species, and ranges in value from zero to one (equally distributed). Statistical analyses were applied to environmental and biotic data, to estimate and test similarity of both environmental data and structure of benthic assemblages within and among control and impacted locations. Non-metric multidimensional scaling ordination (nMDS) (Clarke 1993), based on Bray-Curtis similarity matrix of square root transformed data, was produced to visualize differences in structure of faunal assemblages among samples, in terms of species composition and their relative abundance. The nMDS is dimensionless and represent the samples as points in two-dimensional plot where the distances between points are in the same rank order as the relative similarity of the samples measured by similarity index. A greater distance between points in an nMDS plot indicates a greater dissimilarity between samples. A distance-based permutational analysis of variance (PERMANOVA) (Anderson 2001; McArdle and Anderson 2001) was performed to test for: 1) differences in environmental variables, 2) differences in biodiversity indices and 3) differences in structure of macrobenthic assemblages. The experimental design included three factors: control/impact (fixed, two levels), location (random, five levels, of which four nested in control and one in impact) and area (random, two levels, nested within location). PERMANOVA was based on Euclidean distances for univariate analysis and on Bray-Curtis similarity matrix of square root transformed data to test differences in structure of benthic assemblages. In order to detect taxa most responsible for faunal similarity within impact and control and dissimilarity between impact and control, a similarity percentage (SIMPER) analysis (Clarke 1993) (90% cut off) was carried out. Statistical analyses were done using PRIMER v6 software (Clarke and Gorley 2006), including the add-on package PERMANOVA+ (Anderson et al. 2008).

### 2.3 Ejector preliminary testing

Ejector design has been optimised over the years to achieve the maximum effectiveness with the minimum power consumption. The first result was achieved through a continuous redesign of the ejector geometry, while the second result was implemented through a sophisticated automatic control strategy of the water pumping plant (Bianchini et al. 2014). Moreover, ejector design has been refined to reach a stable near-zero impact condition, i.e. neutral mass balance in the area of influence – the ejector removes as much sediment as it receives. Specific information about the impact of design parameters can be found in Bianchini et al (2014). A new version of the ejector was designed for the Cervia installation: in particular, the number of radial nozzles was optimised, and some modifications were also made to the internal part to reduce pressure losses and to simplify device assembling. The new version of the ejector was preliminary tested in the laboratory of the University of Bologna (Fig. 4): inlet and outlet ejector stream pressures were measured by pressure gauges, while inlet and outlet volumetric flows were measured by level variation in the water and discharge tanks, respectively. Ejector performance is measured through the ratio between the secondary flowrate $Q_S$ (i.e. the flowrate that is sucked in by the ejector, computed as the difference between discharge flowrate $Q_D$ and primary flowrate $Q_P$) and the discharge flowrate $Q_D$. The primary flowrate includes both central nozzle and radial nozzle flowrates, but only the central nozzle is responsible for the suction capacity of the ejector. Moreover, the performance of the ejector was characterised based on the equivalent discharge pipe length, which was simulated in the laboratory by the opening/closing of a manual valve in the discharge pipeline. Different plant configurations were tested, resulting as a combination of the following variables: ejector central nozzle diameter, numbers of ejector radial nozzles, primary flowrate (controlled through a manual valve) and discharge pipeline length.

Once laboratory trials have been concluded, two ejectors were tested in Cervia in July 2017. The ejectors were installed at the harbour inlet and were tested for 10 days in different configurations, while one ejector worked for 15 days continuously at a specific working condition. The field tests (Fig. 5) were carried out with a similar approach to the laboratory one (Fig. 4): two submersible centrifugal pumps were installed in the Marina of Cervia, each one pumping water to one ejector. The pressure was measured before the manual valve to estimate the primary flowrate based on the pump characteristic curve. The discharge rate was computed by measuring the filling time of a floating tank.

**2.4 Permit/authorisation procedure**

Italian legislation on dredging has been subject to continual reforms and the topic remained controversial for a long time. In fact, the need to dredge the bottom of water bodies in order to ensure navigation security or remove dangerous sediments has always been in contrast with: i) the classification of dredged material (waste or non-waste?), ii) the need for possible remediation measures in the same area, and iii) the reuse of sediments as a resource. The European Directive 2008/98/EC clarifies that "*sediments relocated inside surface waters for the purpose of managing waters and waterways or of preventing floods or mitigating the effects of floods and droughts or land reclamation*" are excluded from Waste Directive application. Nevertheless, all dredging operations are subject to environmental permits: more and more attention has been given to the environmental impact of dredging since the Water Framework Directive has been in place. The result is that dredging operations have become more difficult to plan and authorise.

One of the main barriers in technology innovation is usually the legislative barrier: in this specific case, the main issue is how to define the operation of the demo plant, namely whether the demo plant operates as a dredge or not. Since 21$^{st}$ September 2016, a new regulation about dredging operation has been in place in Italy (DM 173/2016). The main merit of the new regulation is that it clarified what can be considered as excluded from being authorised as a dredging operation, in. In particular, sediment "*movements in the harbour area and in the operations of restoration of the beaches*", "*movements in the harbour area*" were defined as "*handling of sediments inside harbour structures for the remodelling activities of the seabed in order to guarantee the moorings practicability, the safety of approach operations or the restoration of navigability, with methods that avoid dispersion of sediments outside the intervention site*". Another issue regarding the demo plant operation is related to the legislative definition of "wastewater discharge" (from D.Lgs. 152/06), which may involve a specific permit for the ejectors and ejector discharge duct installation, as well as for the filter discharge pipeline that is installed in the pumping station of the demo plant.

Both legislative issues were dealt with through a pro-active and positive interaction with the regional environmental agency (ARPAE), which is in charge of issuing both permits (dredging and wastewater discharge) for the demo plant installation and operation.

## 3 Results and discussion

### 3.1 First results of the sea floor integrity monitoring activities

#### *3.1.1 Sediment characterisation*

Before demo plant operation start-up, sediments from the Cervia harbour inlet showed no significant toxicity responses in the alga *Phaeodactylum tricornutum* Boblin, 1897, and in the crustacean *Acartia (Acanthacartia) tonsa* Dana, 1849. Granulometric analysis of sediment showed that fine sand was the dominant fraction in all samples (Fig. 6). In general, both the percentage of mud and the medium sand fraction were higher in the location impacted by dredging and planned to host the demo plant (Fig. 7). The percentage of organic matter and shell debris were also higher in the impacted location (Fig. 7).

Similar changes in sediment composition following dredging, exhibited as the increase of fine deposits at the extraction site, have been widely reported in the literature (Bonsdorff 1983; Seiderer and Newell 1999; Desperez 2000; Sarda et al. 2000; Cooper et al. 2001): these changes can have implications for resident and recolonising fauna, and can lead to the establishment of a benthic community different from the one present before the dredging.

#### *3.1.2 Benthic assemblage characterisation*

Overall, 80 taxa were identified from 44010 specimens of macrofaunal invertebrates analysed, belonging to phyla Mollusca, Arthropoda, Echinodermata, Nemertea, Platyhelminthes, Phoronida and Annelida, with annelid polychaetes being the richest group (34 taxa). In terms of abundance, molluscs were the dominant macrobenthic group in all locations, constituting 96% - 98% of the entire macrobenthic fauna, followed by polychaetes in northern locations and crustaceans in southern and impacted locations. Assemblages at the impacted location were characterised by significantly lower abundance (pseudo F = 26.973; $P = 0.0143$) and species richness (pseudo F = 11.265; $P = 0.0448$) and higher Hill's evenness index (pseudo F = 422.500; $P = 0.0003$) compared to controls (Fig. 8). Hill's species diversity index did not show clear differences between impacted and control assemblages (pseudo F = 0.4603; $P = 0.5506$). Assemblages structures at the impacted location were significantly different (pseudo F = 31.590; $P = 0.0001$) and more variable compared to those at the control ones (Fig. 9). According to the results of SIMPER analysis (see Table A, part A, in supplementary material), species that mostly characterised benthic assemblages of both control and impact locations were three bivalves, *Lentidium mediterraneum* (O. G. Costa, 1830), *Donax semistriatus* (Poli, 1795) and *Chamelea gallina* (Linnaeus, 1758). The relatively high dissimilarity (64.53%) in species composition and abundance between impact and control was mainly due to a drastic decrease in abundance of the same three bivalves in the impacted locations, and to a lesser extent due to lower species diversity in the impacted location (see Table A, part B, in supplementary material).

Results of the survey showed that macrofaunal assemblages in the study area are in accordance with the shallow subtidal soft-bottom communities reported previously along the Emilia-Romagna coast, dominated by bivalve *L. mediterraneum* and characterised by the presence of the bivalves *D. semistriatus* and *C. gallina* and the gastropode *Tritia neritea* Linnaeus, 1758 (Bertasi et al. 2007). The macrobenthic composition was characterised by the presence of a few highly abundant species and many species with very low frequency, a pattern already observed from the similar assemblages in the northern Adriatic Sea (Occhipinti-Ambrogi et al. 2005). The results indicate that dredging activities had negative impacts both on species richness and abundance and lead to changes in structure of benthic communities. The observed patterns are presumably a combination result of both long term changes due to the periodic annual dredging and actual response of assemblages to dredging operations that took place only a couple of weeks before the sampling. Three bivalve species that mostly characterised benthic assemblages at all locations (*L. mediterraneum*, *C. gallina* and *D. semistriatus*), and showed a drastically lower abundance in the impacted location, are species sensitive to disturbance, characterised by relatively long life, slow growth and high biomass (Simboura and Zenetos 2002). Communities that are characterised by sensitive species tend to show considerable change and slow recovery after dredging (Kotta et al. 2009).

Fish fauna in the area may include different pelagic and benthic species; however, the flathead grey mullet, *Mugil cephalus* (Linnaeus, 1758), was the only species that was observed in video samples, and was recorded only in the impacted location, with an average of 1.29 (±0.4) individuals per minute in area 1 (I1), planned to host the ejectors, and 4.5 (±1.7) individuals per minute in area 2 (I2), planned to receive sediment delivering. This species is a diurnal bottom feeder, feeding mainly on diatoms, algae, copepods and organic matter (Islam et al. 2009; Mondal et al. 2015). Dredging activities, that occurred a few days before sampling, may have brought the organic matter from the deeper sediment strata to the surface, which could have attracted mullets that feed on it. Moreover, mullets are generally well known to be extremely abundant in ports and marinas where they can find greater food resources.

### 3.2 Field test results

In the real environment, the ejectors showed similar performances to the ones achieved in the laboratory. The tests therefore allowed to select the ejector able to guarantee the best performances in the most critical conditions, which correspond to the worst sea weather conditions, i.e. sea storms with North-East waves direction. On the basis of previous experience (Bianchini et al. 2014), a mean sand flowrate of about 2 $m^3h^{-1}$ in the discharge flowrate for each ejector is required in critical conditions to balance the sand transported by the waves. Results and figures cannot be shown in detail due to restrictions based on the intellectual properties of the technology.

The selected ejector was tested for 15 days in the following operating condition: primary water feeding flowrate of about 27 $m^3h^{-1}$, working pressure of about 2.4 bar and a discharge pipeline characterised by 60 metres in length. This operating condition corresponds to a peak sand flowrate at the discharge pipeline of about 2 $m^3h^{-1}$ (whole discharge flowrate is about 34 $m^3h^{-1}$) and a water pump power consumption of about 3.5 kW. After 15 days of continuous operation, the ejector, installed at a water depth of 2.6 m, was able to reach and maintain a water depth of 3.4 m. The measured influence area had a diameter of about 5-7 m. Obviously, such a working condition is not expected to be constant, and so the related power consumption of the plant is estimated to be considerably lower. In fact, by lowering the ejector primary water flowrate to 25 $m^3h^{-1}$ it is possible to reduce both ejector suction capacity as well as power consumption. The plant operation can thus be adapted to the current environmental condition by controlling the primary water flowrate that is used to feed the ejectors.

## 3.3 Demo plant design

### *3.3.1 Analysis of past bathymetries*

Through the analysis of the last 10 years' bathymetries it was possible to verify how the natural sand transport is interrupted by the docks of the harbour channel. See, for example, the two bathymetries that are shown in Figure A (supplementary material): on the left side are the bathymetries plotted after sediment handling through propellers (May 2009), while on the right side the bathymetries seven months later (December 2009). The red lines in Figure A indicate the – 2.00 m of water depth, which is considered as the minimum acceptable value for safety navigation at the harbour inlet of Cervia. Figure A clearly shows how the sand moves from North to South by turning around the northern dock (a vortex can be seen) and then entering the harbour inlet. The same trend can be observed in the bathymetries from 2010 to 2018.

The challenge is to identify the most critical area of siltation, since, as observed in the previous installations (Bianchini et al. 2014), if siltation is avoided in that location, the siltation process should not proceed in the sediment natural transport direction. Through this approach it is possible to maximise the efficacy of the plant by keeping the number of ejectors installed to a minimum, which is a relevant contributing parameter to the demo plant investment cost. Figure B (supplementary material) shows how the demo plant is intended to work in the harbour inlet area: a first area of influence of about 30 m x 20 m (i.e. the rectangular area in Figure B) is strongly influenced by ejector operation, while a second semi-circular area of about 40-50 m from first area's centre (i.e.

the semi-circular area in Figure B) is still influenced by ejector operation, but with longer timings. The demo plant achieves sand by-passing from the northern to the southern dock and avoids sediment siltation in the harbour inlet. The sediment that is transported by the principal natural conveying direction or by relevant weather events like sea storms in the first area of influence is directly sucked in by the ejectors and discharged 60 m away from each ejector. That distance was chosen since it is the minimum required to get beyond the southern dock line. The sediment that is transported in the second influence area slowly slides towards the first area of influence. The expected impact of the demo plant is to avoid sediment siltation at the harbour inlet through a sand by-pass system that pushes the sediment in the natural direction, i.e. the direction that the sediment would take if the docks were not installed.

On the basis of ejector characteristics and preliminary tests results and sediment characterisation, 10 ejectors are needed to cover such an area, which measures about 1,600 $m^2$. Based on historic bathymetry analysis, a mean yearly sediment rate of 3,000-4,000 $m^3$ of sand can be expected in that area.

### *3.3.2 Demo plant design and installation*

The demo plant consists of 10 ejectors and also includes a fully automated and remotely accessible pumping station equipped with auto-purging filters. The Piping and Instrumentation Diagram (P&ID) of the pumping plant is schematically shown in Figure C (supplementary material), where only one ejector line is drafted. There are two pumps, each one feeding five ejectors. Each pumping line has an auto-purging disk filter: the auto-purging cycle is activated once the pressure drop in the filter reaches a certain level. The total pumped water flowrate is controlled by an inverter, while the flowrate for each ejector feeding pipeline is balanced through electrovalves. An air compressor can be used to inject compressed air in the line to easily identify the position of the ejectors on the seabed. The total installed power is about 80 kW. A local meteorological station has been installed to relate plant operation with sea weather conditions.

ARPAE stated through a written technical opinion that the actions exerted on the seabed by the demo plant comply with the definition of "*remodelling*" stated in DM 173/2016. Hence, they are not regarded as dredging actions but, rather, as sediment management operations within the same water basin. Therefore, according to Italian law, the demo plant does not need any "dredging-like" authorisation or permit. Furthermore, ARPAE also provided a written technical opinion regarding the discharge points of the demo plant, that are i) water jets out of the ejector central nozzle, ii) water-sediment mixture flowrate out of the ejector discharge pipeline and iii) filter discharge pipeline of the water pumping station. ARPAE stated that all these discharge points cannot be classified as "wastewater discharge" due to the operation mode of the demo plant.

## 4 Conclusions

The MARINAPLAN PLUS LIFE project aims to demonstrate the effectiveness of a novel sediment by-passing plant to be installed at the Cervia harbour inlet. The project, started in October 2016, is now entering the decisive phase, since the demo plant is under commissioning. Nevertheless, many activities have already been completed, including the preliminary testing (in the laboratory and in the field) of the ejectors, the completion of the authorisation/permit procedures, the characterisation of the sediment to be moved and of the existing flora and fauna. The preliminary test results showed that one ejector should guarantee a sediment removal capacity of about $2 m^3 h^{-1}$ with a power consumption of about 3.5 kW, with an area of influence up to 5-7 m in 15 days of operation. The technology has been recognized as not comparable with dredging, meaning that the authorization procedure for the plant installation does not have to comply with dredging legislation (i.e. Italian Law Decree 172/2016). Furthermore, the environmental assessment in the study area showed how the benthic fauna has been greatly negatively affected by the dredging operations that have been carried out over the years at the port inlet.

The next steps are to assess the possible environmental impacts of the demo plant and to compare them with dredging effects. For this purpose, two sea floor integrity monitoring surveys are planned after the demo plant operation start-up. They will make it possible to detect eventual changes in sediment characteristics and benthic communities structures. Underwater noise will also be measured. Moreover, the demo plant technical features will be demonstrated at industrial scale: the demo plant can be automatically operated and a remote control can be used to continuously by-pass sediment from the harbour inlet, i.e. 24 hours a day and 7 days per week. An important consequence of this characteristic is the certainty of seabed maintenance costs: in fact, the adoption of the plant allows for a precise planning of seabed maintenance costs, solely linked to the plant's operating costs, regarding dredging activities as extraordinary – and not ordinary - maintenance interventions. This means that an important result of the LIFE MARINAPLAN PLUS project will also be the identification of operation and maintenance costs.

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## References


Amati G, Saccani C (2005) Experimental plant for sediment management in harbours' areas (in Italian). In: Proceedings of the XXXII National Conference on Italian Plant Engineering, 6-7 October, Rimini, Italy

Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. Aust J Ecol 26:32–46

Anderson MJ, Gorley RN, Clarke KR (2008) PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth, UK

ARPAE (2016) Status of the Emilia-Romagna coast at 2012 - Erosion and defense interventions (Stato del litorale Emiliano-romagnolo al 2012 – Erosione e interventi di difesa, in Italian).

Bertasi F, Colangelo MA, Abbiati M, Ceccherelli VU (2007) Effects of an artificial protection structure on the sandy shore macrofaunal community: the special case of Lido di Dante (Northern Adriatic Sea). Hydrobiologia 586:277–290

Bianchini A, Pellegrini M, Saccani C (2014) Zero environmental impact plant for seabed maintenance. In: Proceedings of the International Symposium on Sediment Management I2SM, 17-19 September, Ferrara, Italy

Bianchini A, Cento F, Guzzini A, Pellegrini M, Saccani C (2019) Sediment management in coastal infrastructures: techno-economic and environmental impact assessment of alternative technologies to dredging. J Environ Manage 248:109332. https://doi.org/10.1016/j.jenvman.2019.109332

Bonsdorff E (1983) Recovery potential of macrozoobenthos from dredging in shallow brackish waters. Oceanol Acta 4:27–32

Boswood PK, Murray RJ (2001) World-wide sand by-passing systems: data report. Conservation technical report n°20, Environmental Protection Agency, Queensland Government

Bray RN, Bates AD, Land JM (1996) Dredging: A Handbook for Engineers. Butterworth-Heinemann, Okford

Bruun P (1996) Navigation and sand bypassing at inlets: technical management and cost analysis. J Coastal Res 23:1139-119

Clarke KR (1993) Nonparametric multivariate analyses of changes in community structure. Aust J Ecol 18:17–143

Clarke KR, Gorley RN (2006) PRIMER v6: User Manual/Tutorial. Plymouth: PRIMER-E. 192 pp

Cooper KM, Curtis M, Wan Hussin WMR, Barrio Froján CRS, Defew EC, Nye V, Paterson DM (2011) Implications of dredging induced changes in sediment particle size composition for the structure and function of marine benthic macrofaunal communities. Mar Pollut Bull 62:2087–2094

Cutroneo L, Castellano M, Ferranti MP, Povero P, Tucci S, Capello M (2013) Use of optical and acoustic instruments to study the turbid plumes generated by three different types of dredges during dredging activities inside and outside of a port. J Soils Sediments 13:1645-1654. https://doi.org/10.1007/s11368-013-0756-5

Dean RG, Dalrymple RA (2004) Coastal processes with engineering applications. Cambridge University Press, Cambridge

Desprez M (2000) Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel: short-and long-term post-dredging restoration. ICES J Mar Sci 57:1428–1438

Hill MO (1973) Diversity and evenness: a unifying notation and its consequences. Ecology 54:427–432

Islam R, Hossain MB, Das NG, Rafi RUN (2009) Food and feeding behaviour of grey mullet, *Mugil cephalus* (L), of Bangladesh coastal water. Bangl J Progr Sci Tech 7:56–61

Kotta J, Herkül K, Kotta I, Orav-Kotta H, Aps R (2009) Response of benthic invertebrate communities to the large-scale dredging of Muuga Port. Est J Ecology 58:286–296

Mali M, Dell'Anna MM, Mastrorilli P, Damiani L, Piccinni AF (2017) Assessment and source identification of pollution risk for touristic ports: Heavy metals and polycyclic aromatic hydrocarbons in sediments of 4 marinas of the Apulia region (Italy). Mar Pollut Bull 114:768-777

Manap N, Voulvoulis N (2015) Environmental management for dredging sediments – The requirement of developing nations. J Environ Manage 147:338–348

MATTM, ICRAM (2001) Reference for Analytical Methodologies (in Italian)

McArdle BH, Anderson MJ (2001) Fitting multivariate models to community data: A comment on distance-based redundancy analysis. Ecology 82:290–297

McNair ECJ (1976) A sand by-passing system using a jet pump. In: ASCE, Coastal Engineering. Proceedings of Fifteenth Coastal Engineering Conference, July 11-17, Honolulu, Hawaii (USA)

Mondal A, Chakravortty D, Mandal S, Bhattacharyya SB, Mitra A (2015) Feeding Ecology and Prey Preference of Grey Mullet, *Mugil cephalus* (Linnaeus, 1758) in Extensive Brackish Water Farming System. J Marine Sci Res Dev 6:178-183. https://dx.doi.org/10.4172/2155-9910.1000178

Occhipinti-Ambrogi A, Savini D, Forni G (2005) Macrobenthos community structural changes off Cesenatico coast (Emilia Romagna, Northern Adriatic), a six-year monitoring programme. Sci Total Environ 353:317–328

Ohimain EI, Andriesse W, van Mensvoort MEF (2004) Environmental impacts of abandoned dredged soils and sediments. J Soils Sediments 4:59-65. https://doi.org/10.1007/BF02990830

Ponti M, Pasteris A, Guerra R, Abbiati M (2009) Impacts of maintenance channel dredging in a northern Adriatic coastal lagoon. II: Effects on macrobenthic assemblages in channels and ponds. Estuar Coast Shelf S 85:143-150. https://doi.org/10.1016/j.ecss.2009.06.027

Ragnarsson SA, Thorarinsdóttir GG, Gunnarsson K (2015) Short and long-term effects of hydraulic dredging on benthic communities and ocean quahog (Arctica islandica) populations. Mar Environ Res 109:113-123. https://doi.org/10.1016/j.marenvres.2015.05.003

Sarda R, Pinedo S, Gremare A, Taboada S (2000) Changes in the dynamics of shallow sandy bottom assemblages due to sand extraction in the Catalan Western Mediterranean Sea. ICES J Mar Sci 57:1446–1453

Schaanning MT, Harman C, Staalstrøm A (2011) Release of dissolved trace metals and organic contaminants during deep water disposal of contaminated sediments from Oslo harbour, Norway. J Soils Sediments 11:1477-1489. https://doi.org/10.1007/s11368-011-0436-2

Seiderer LJ, Newell RC (1999) Analysis of the relationship between sediment composition and benthic community structure in coastal deposits: implications for marine aggregate dredging. ICES J Mar Sci 56:757–765

Simboura N, Zenetos A (2002) Benthic indicators to use in Ecological Quality classification of Mediterranean. Mediterr Mar Sci 3/2:77–111

Stewart M (2019) Special purpose pumps. In: Stewart M (ed) Surface Production Operations Volume IV - Pump and Compressor Systems: Mechanical Design and Specification, 1st edn. Gulf Professional Publishing, Cambridge, pp 441-455. https://doi.org/10.1016/B978-0-12-809895-0.00006-5

Suedel BC, Lutz CH, Clarke JU, Clarke DG (2012) The effects of suspended sediment on walleye (Sander vitreus) eggs. J Soils Sediments 12:995-1003. https://doi.org/10.1007/s11368-012-0521-1

Torres RJ, Abessa DMS, Santos FC, Maranho NA, Davanso MB, do Nascimento MRL, Mozeto AA (2009) Effects of dredging operations on sediment quality: contaminant mobilization in dredged sediments from the Port of Santos, SP, Brazil. J Soils Sediments 9:420-432. https://doi.org/10.1007/s11368-009-0121-x

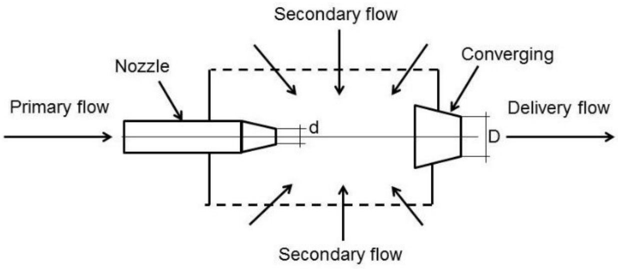


Figure 1. Sketch of the ejector (Bianchini et al. 2014)


Figure 2. Cervia position and harbour aerial picture of the study area.

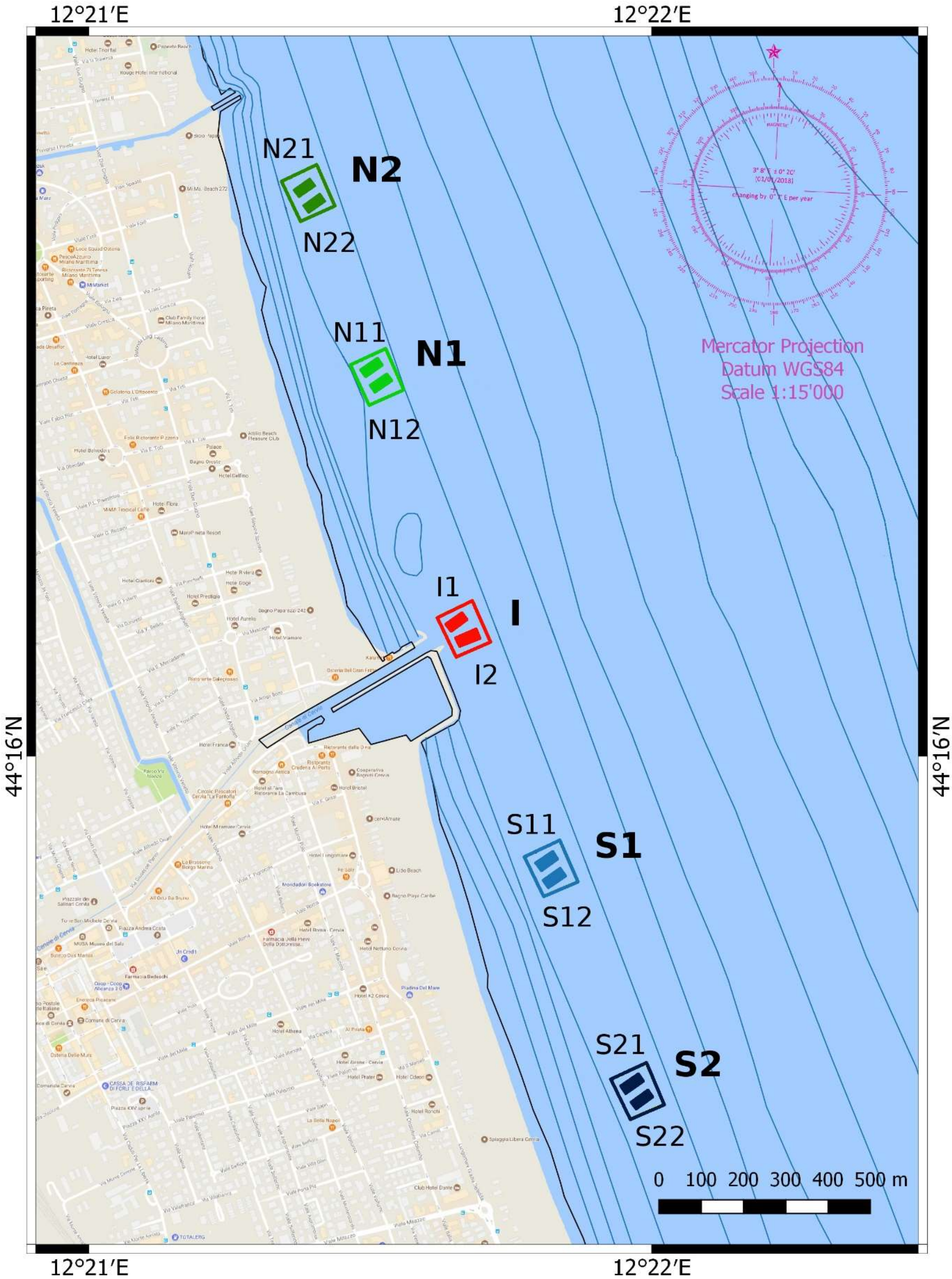


Figure 3. Map of sampling locations (Mercator projection, geodetic datum WGS84). N11 and N12 = areas within location North 600 m (N1), N21 and N22 = areas within location North 1200 m (N2), S11 and S12 = areas within location South 600 m (S1), S21 and S22 = areas within location South 1200 m (S2), I1 and I2 = areas within location impact (I)

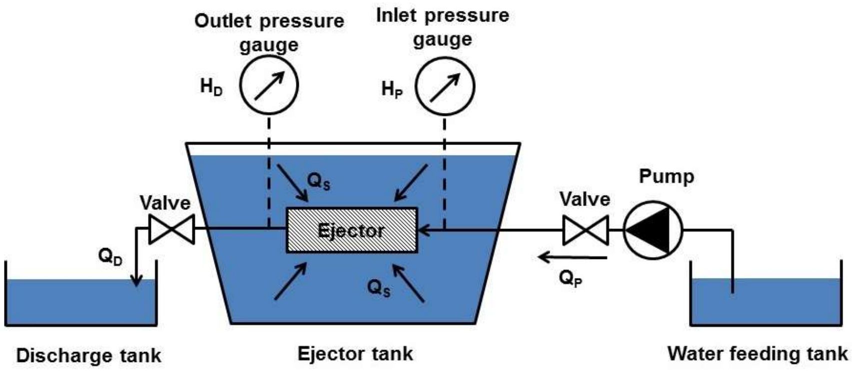


Figure 4. Laboratory testing equipment for ejectors (Bianchini et al. 2014)

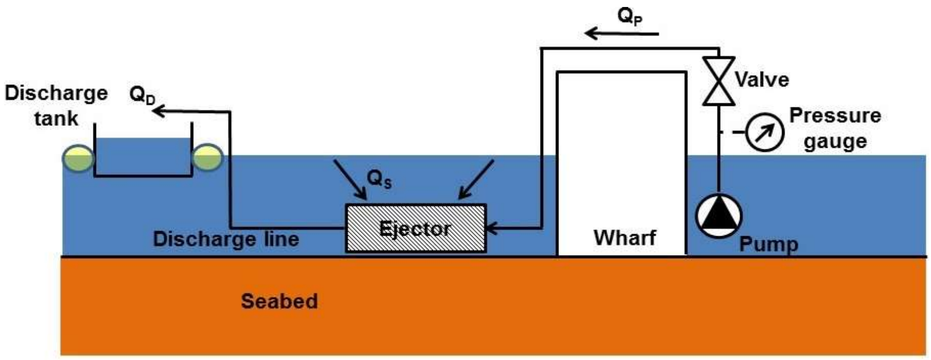


Figure 5. Field testing equipment for ejectors

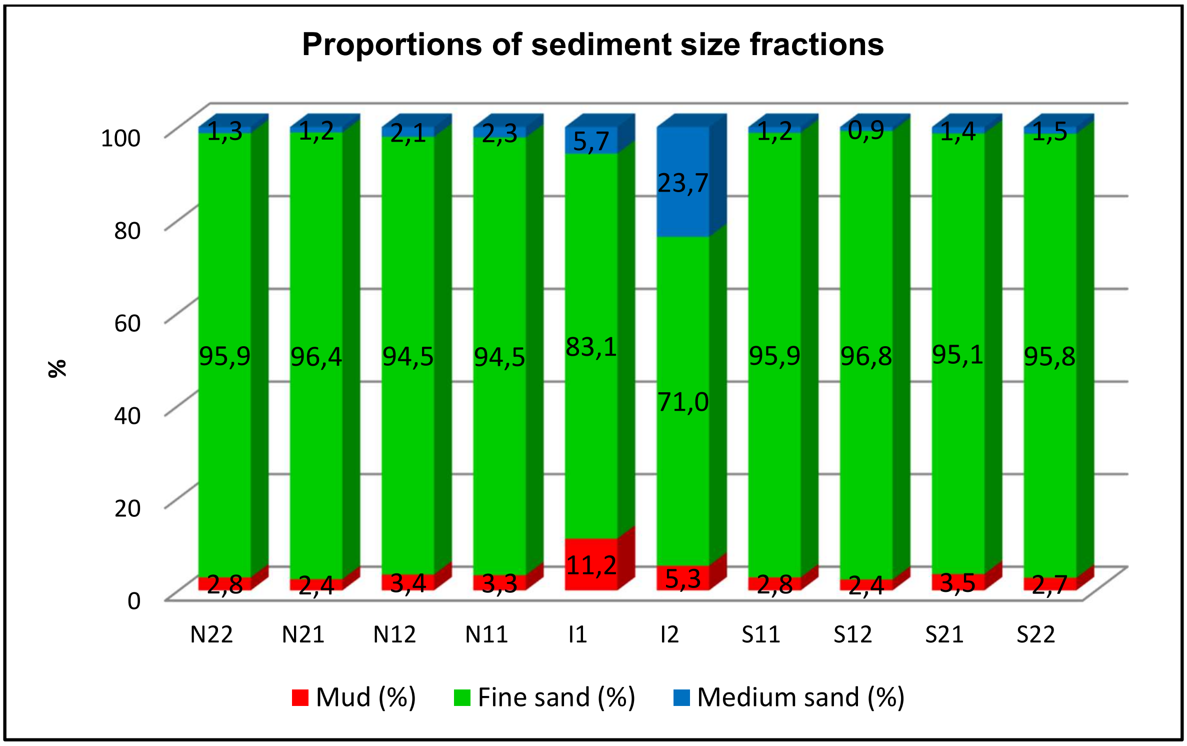


Figure 6. Mean percentage of sediment size fractions in each research area. N11 and N12 = areas within North 600 m, N21 and N22 = areas within North 1200 m, S11 and S12 = areas within South 600 m, S21 and S22 = areas within South 1200 m, I1 and I2 = areas within impact

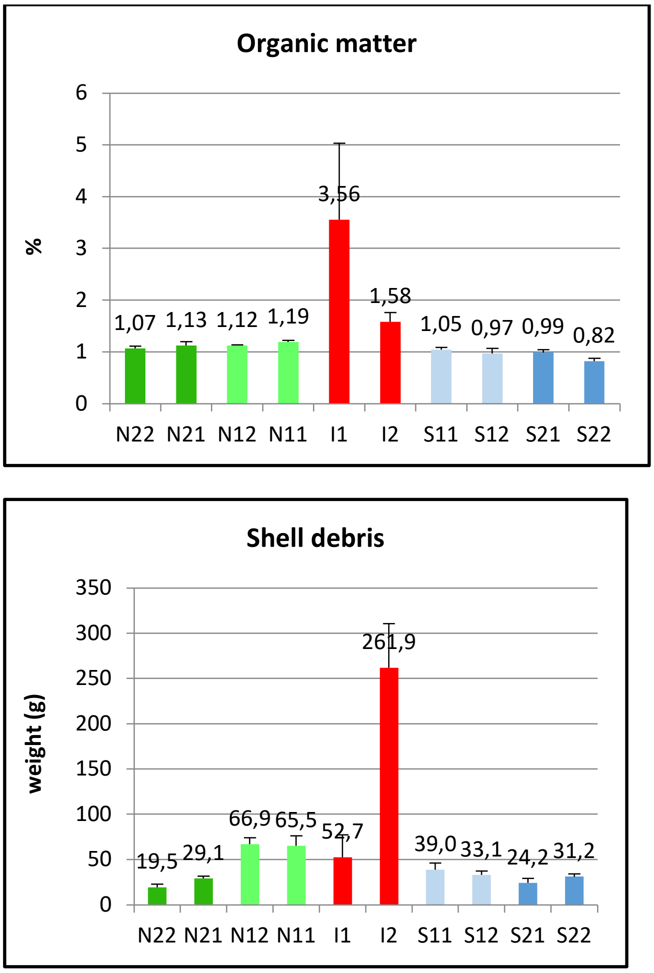


Figure 7. Mean (±standard error) percentage of organic matter and mass of shell debris in sediment at each research area. N11 and N12 = areas within North 600 m, N21 and N22 = areas within North 1200 m, S11 and S12 = areas within South 600 m, S21 and S22 = areas within South 1200 m, I1 and I2 = areas within impact

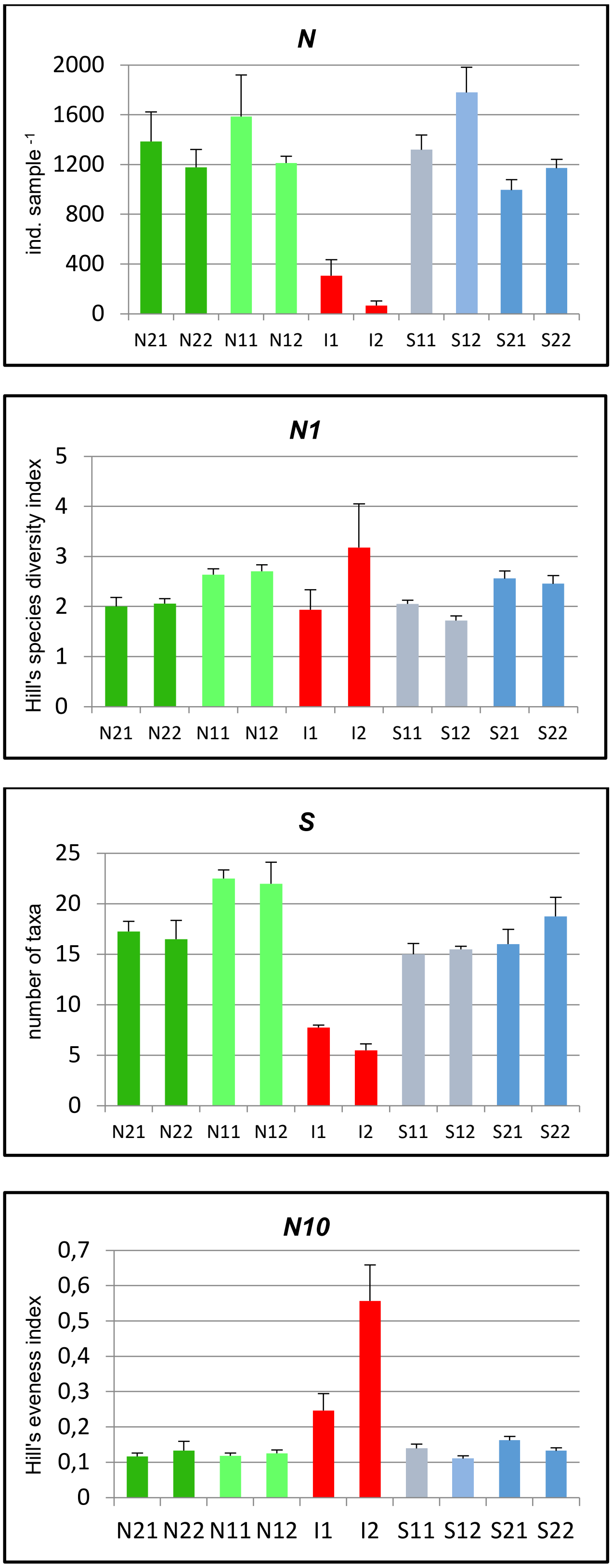


Figure 8. Mean (± standard error) total abundance (N), species richness (S), Hill's species diversity index (N1) and Hill's evenness index (N10) at each research area. N11 and N12 = areas within North 600 m, N21 and N22 = areas within North 1200 m, S11 and S12 = areas within South 600 m, S21 and S22 = areas within South 1200 m, I1 and I2 = areas within impact

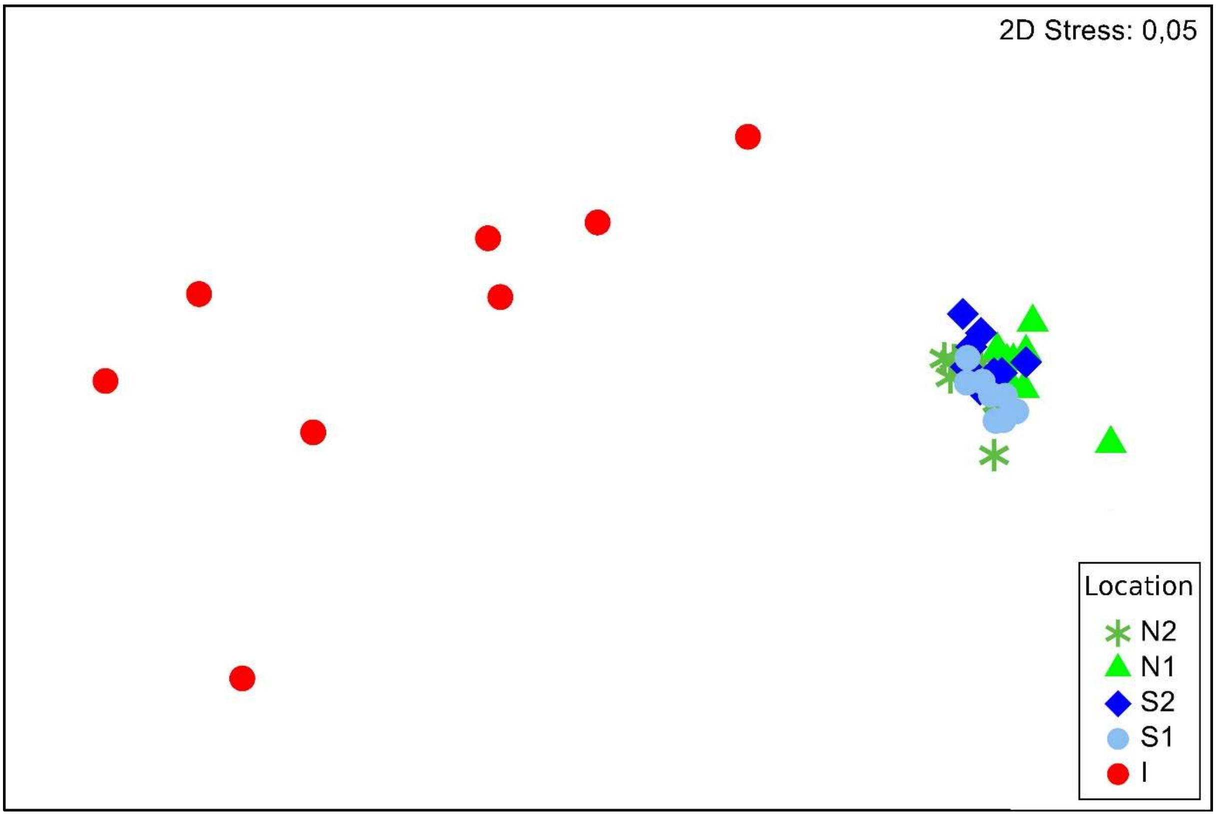


Figure 9. Non-metric MDS ordination plot based on Bray-Curtis similarity of square root transformed data, comparing structure of benthic communities between samples on impacted and control locations. N1 = North 600 m, N2 = North 1200 m, S1 = South 600 m, S2 = South 1200 m, I = impact

**Table 1**. Dredging and/or sediment handling through boat propellers or dredgers in Cervia harbour from 2009 to 2015.

| **Year** | **Month** | **Operation** | **Quantity ($m^3$)** | **Duration (days)** | **Cost (€)** |
|---|---|---|---|---|---|
| 2009 | Jan-Feb | Dredging | 20000 | - | 180000 |
| 2009 | May | Propellers | - | 12 | 100000 |
| 2010 | Jan-Mar | Propellers | - | 12 | 100000 |
| 2011 | Jan | Propellers | - | 6 | 52000 |
| 2011 | Nov | Propellers | - | 6 | 52000 |
| 2012 | Apr | Propellers | - | 3 | 23400 |
| 2013 | May-Jun | Dredging | 16950 | - | 150000 |
| 2014 | Feb-Apr | Propellers | - | 4 | 20000 |
| 2014 | Feb-Apr | Dredging | 51200 | - | 500000 |
| 2015 | Jan-Feb | Dredging | 10000 | - | - |
| 2015 | Apr-May | Dredging | 23400 | - | 180000 |