



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

ARCHIVIO ISTITUZIONALE DELLA RICERCA

Alma Mater Studiorum Università di Bologna Archivio istituzionale della ricerca

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

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Sustainable sediment management in coastal infrastructures through an innovative technology: preliminary results of the MARINAPLAN PLUS LIFE project / Pellegrini, Marco; Abbiati, Marco; Bianchini, Augusto; Colangelo, Marina Antonia; Guzzini, Alessandro; Mikac, Barbara; Ponti, Massimo; Preda, Giovanni; Sacconi, Cesare; Willemsen, Albert. - In: JOURNAL OF SOILS AND SEDIMENTS. - ISSN 1439-0108. - ELETTRONICO. - 20:(2020), pp. 2685-2696. [10.1007/s11368-019-02546-6]

Availability:

This version is available at: <https://hdl.handle.net/11585/711419> since: 2020-08-06

Published:

DOI: <http://doi.org/10.1007/s11368-019-02546-6>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).
When citing, please refer to the published version.

(Article begins on next page)

This is a post-peer-review, pre-copyedit version of an article published in:

Journal of Soils and Sediments

The final authenticated version is available online at:
<https://doi.org/10.1007/s11368-019-02546-6>

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

When citing, please refer to the published version.

1 SEDIMENTS AS A DYNAMIC NATURAL RESOURCE - FROM CATCHMENT TO OPEN SEA
2

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

5

6 **Marco Pellegrini¹ • Marco Abbiati^{5,6,7,8} • Augusto Bianchini¹ • Marina Colangelo^{4,5,7} • Alessandro Guzzini¹**
7 **• Barbara Mikac⁵ • Massimo Ponti^{4,5,7} • Giovanni Preda² • Cesare Saccani¹ • Albert Willemsen³**

8

9 ¹Department of Industrial Engineering, University of Bologna, Viale Risorgimento 2 – 40100, Bologna, Italy

10 ²Trevi SpA, Via Dismano 5819 – 47522, Cesena, Italy

11 ³Environment Consultant, ICOMIA, Brigade Pironlaan 132 - 1080, Brussels, Belgium

12 ⁴Department of Biological, Geological and Environmental Sciences, University of Bologna, via S. Alberto 163 -
13 48120, Ravenna, Italy

14 ⁵Interdepartmental Research Centre for Environmental Sciences, University of Bologna, Via S. Alberto 163 –
15 48120, Ravenna, Italy

16 ⁶Department of Cultural Heritage, University of Bologna, Via degli Ariani 1 – 48120, Ravenna, Italy

17 ⁷National Interuniversity Consortium for Marina Science, Piazzale Flaminio, 9 – 00196, Rome, Italy

18 ⁸Marine Science Institute – CNR, Via Piero Gobetti, 101 – 40129, Bologna, Italy

19

20

21 ✉ Marco Pellegrini

22 marco.pellegrini3@unibo.it

23

24 **Abstract**

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

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

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

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

43

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

46

47 **1 Introduction**

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

62 The MARINAPLAN PLUS LIFE project started in October 2016 and foresees the construction of a sediment by-
63 passing plant in the harbour channel inlet of Cervia (Italy), which is located in the Adriatic Sea and can be
64 considered as a representative siltation case study for Middle-North Adriatic Sea harbours and marinas. Trevi SpA
65 is the project coordinator, whereas Cervia Municipality, the University of Bologna and ICOMIA are project
66 partners. The core of a sediment by-passing plant is the jet pump. The jet pump is a well-known and reliable
67 technology which has several applications in different fields (Stewart 2019). In a sediment by-passing plant, the
68 jet pump is placed on the seabed and transfers momentum from a high speed primary water jet flow to a secondary
69 flow that is a mixture of water and of the surrounding sediment. The sediment-water mixture is then conveyed
70 through a pipeline and discharged in an area where the sediment can be picked up again from the main seawater
71 current or where it is not an obstacle for navigation. The technology is reliable since it has been applied starting
72 from the '70s for coastal application (McNair 1976), it requires limited personnel, is extremely portable and can
73 be assembled at reasonable cost. The sediment by-passing technology tested within the MARINAPLAN PLUS
74 LIFE project has two important novelties: the first is that the main element of the plant, called “*ejector*” (Fig. 1),
75 is an open jet pump (i.e. without closed suction chamber and mixing throat) with a converging section instead of
76 a diffuser and a series of nozzles positioned circularly around the ejector. The technology has been under

77 development since 2001 and has already been applied in two experimental plants in Italy (Amati and Saccani 2005;
78 Bianchini et al. 2014): the ejector works on a limited circular area created by the pressurized water outgoing from
79 the central and circular nozzles, whose diameter depends on the sediment characteristics such as, for example, the
80 repose angle. By ejector integration in series and in parallel it is possible to create or to maintain a seaway.

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

86 The paper shows the preliminary results of the MARINAPLAN PLUS LIFE project. In particular, the paper
87 focuses on the difficulties that the project development faced in the design phase of the demo plant, including the
88 permit and authorisation process. The paper includes the analysis of the preliminary field tests carried out in July
89 2017, the description of the monitoring plan and the first environmental monitoring actions carried out. This
90 information is of paramount importance to fully validate the technology and to demonstrate its efficacy and
91 sustainability both in economic and environmental terms.

92

93 **2 Materials and methods**

94 **2.1 Site description**

95 Cervia is a municipality counting about 30,000 inhabitants. Nevertheless, as normal on the Emilia-Romagna region
96 coast, Cervia is characterised by a dramatic increase in population during the summer holiday season. The Marina
97 of Cervia is located on the North-East side of the old harbour (Fig. 2), reserved for recreational craft, consisting of
98 a dock with eight piers. The Marina has a capacity of 300 boats with a maximum length of 22 m. Cervia harbour
99 is affected by a cyclic problem of inlet silting. The technological solutions adopted until now, including seasonal
100 dredging and/or sand underwater re-suspension by boat propellers, as well as docks lengthening (completed in
101 2009), have not solved the siltation problem: as highlighted by Table 1, from 2009 to 2015 the Municipality
102 invested about 1.3 million Euro in dredging and sediment handling with propellers (i.e. a mean yearly cost of
103 185,000 Euro).

104 Natural sand transport is present alongside the coast line, moving from North to South, as confirmed by regional
105 studies (ARPAE 2016). Nevertheless, a more in-depth analysis was needed to properly design the demo plant: in
106 particular, the ejector placement is defined to prevent sediment siltation in the most critical area, while the ejector

107 number is evaluated based on the estimated sediment quality/composition and quantity to be removed from that
108 area. The most critical area for sediment siltation and the estimation of sediment quantity to be removed can both
109 be identified through bathymetries analysis. The siltation phenomena in Cervia harbour is monitored by the
110 Municipality through seasonal bathymetries. Since 2009 (after dock lengthening) bathymetries have been carried
111 out through a digital hydrographic ultrasound system with narrow emission cone, preliminary calibration and
112 differential GPS Trimble positioning system; the resulting error is estimated as not exceeding 3 cm. So, the siltation
113 phenomena at the harbour inlet can be evaluated on a robust historical database.

114

115 **2.2 Monitoring plan**

116 Literature data already demonstrated that a sand by-passing plant can be more economical than dredging (Bruun
117 1996; Boswood and Murray 2001; Dean and Dalrymple 2004; Bianchini et al. 2019), even if operation and
118 maintenance costs are usually based on estimation more than on real data. One of the objectives of the
119 MARINAPLAN PLUS LIFE project is to measure the operation and maintenance costs over a period of at least
120 12 months. The efficacy of the demo plant will be monitored through bathymetries in the ejector area, while the
121 efficiency of the demo plant will be assessed through power consumption.

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

130 Possible impacts of the demo plant on sediment characteristics, benthic macroinvertebrates and fish assemblages
131 need to be assessed simultaneously at a variety of spatial scales, encompassing the full extent of the environmental
132 variability of the area where the ejectors are positioned. Sampling sites are located in one putatively impacted
133 location in front of the port of Cervia (location I; 44° 16.162' N, 12° 21.667' E) and in four control locations,
134 placed 600 m (location N1; 44° 16.484' N, 12° 21.512' E) and 1200 m (location N2; 44° 16.718' N, 12° 21.390'
135 E) north and 600 m (location S1; 44° 15.857' N, 12° 21.822' E) and 1200 m (location S2; 44° 15.573' N, 12°
136 21.976' E) south of the impact location respectively (Fig. 3). Two sampling areas (about 800 m² each) are defined

137 within every location, 20-30 m apart. The two areas within the putatively impacted location are represented by the
138 sediment removing and discharging areas, i.e. the ejectors and ejector discharge areas. In May 2018, i.e. one year
139 before demo plant operation and a few weeks after a dredging operation at the harbour inlet, four replicated samples
140 of marine sediment and fauna were manually taken at each sampling area by scientific SCUBA divers, using an
141 aluminium frame (23.5×13.5 cm). Laboratory analyses encompassed sediment grain size (percentage of mud (<63
142 µm), fine sand (63-250 µm) and medium sand (> 250 µm) fractions), percentage of organic matter, dry weight of
143 shell debris and benthic macrofauna determination to the lowest possible taxonomic level (after sieving on 0.5 mm
144 mesh sieve). Fish assemblages were sampled by GoPro Hero 5 video cameras randomly placed within each study
145 area. High definition (Full-HD) 30 minutes digital videos were recorded for each video camera deployment. Each
146 video was further split into four sections long seven to eight minutes, further considered as replicates.

147 For each replicate of benthic samples, indices of macrofaunal assemblage diversity, namely species richness (S),
148 total abundance (N), Hill's species diversity index ($N1$; $N1 = \text{Exp } H'$, where H' is the Shannon index based on
149 natural logarithm) and Hill's evenness index ($N10$; $N10 = N1/S$), were calculated. Hill's diversity index gives the
150 number of species that would have been found in the sample if all the species had been equally abundant (Hill
151 1973). Evenness indicates the distribution of the individuals among species, and ranges in value from zero to one
152 (equally distributed). Statistical analyses were applied to environmental and biotic data, to estimate and test
153 similarity of both environmental data and structure of benthic assemblages within and among control and impacted
154 locations. Non-metric multidimensional scaling ordination (nMDS) (Clarke 1993), based on Bray-Curtis similarity
155 matrix of square root transformed data, was produced to visualize differences in structure of faunal assemblages
156 among samples, in terms of species composition and their relative abundance. The nMDS is dimensionless and
157 represent the samples as points in two-dimensional plot where the distances between points are in the same rank
158 order as the relative similarity of the samples measured by similarity index. A greater distance between points in
159 an nMDS plot indicates a greater dissimilarity between samples. A distance-based permutational analysis of
160 variance (PERMANOVA) (Anderson 2001; McArdle and Anderson 2001) was performed to test for: 1)
161 differences in environmental variables, 2) differences in biodiversity indices and 3) differences in structure of
162 macrobenthic assemblages. The experimental design included three factors: control/impact (fixed, two levels),
163 location (random, five levels, of which four nested in control and one in impact) and area (random, two levels,
164 nested within location). PERMANOVA was based on Euclidean distances for univariate analysis and on Bray-
165 Curtis similarity matrix of square root transformed data to test differences in structure of benthic assemblages. In
166 order to detect taxa most responsible for faunal similarity within impact and control and dissimilarity between

167 impact and control, a similarity percentage (SIMPER) analysis (Clarke 1993) (90% cut off) was carried out.
168 Statistical analyses were done using PRIMER v6 software (Clarke and Gorley 2006), including the add-on package
169 PERMANOVA+ (Anderson et al. 2008).

170

171 **2.3 Ejector preliminary testing**

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

191 Once laboratory trials have been concluded, two ejectors were tested in Cervia in July 2017. The ejectors were
192 installed at the harbour inlet and were tested for 10 days in different configurations, while one ejector worked for
193 15 days continuously at a specific working condition. The field tests (Fig. 5) were carried out with a similar
194 approach to the laboratory one (Fig. 4): two submersible centrifugal pumps were installed in the Marina of Cervia,
195 each one pumping water to one ejector. The pressure was measured before the manual valve to estimate the primary

196 flowrate based on the pump characteristic curve. The discharge rate was computed by measuring the filling time
197 of a floating tank.

198

199 **2.4 Permit/authorisation procedure**

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

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

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

225

226 **3 Results and discussion**

227 **3.1 First results of the sea floor integrity monitoring activities**

228 **3.1.1 Sediment characterisation**

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

235 Similar changes in sediment composition following dredging, exhibited as the increase of fine deposits at the
236 extraction site, have been widely reported in the literature (Bonsdorff 1983; Seiderer and Newell 1999; Desprez
237 2000; Sarda et al. 2000; Cooper et al. 2001): these changes can have implications for resident and recolonising
238 fauna, and can lead to the establishment of a benthic community different from the one present before the dredging.

239

240 **3.1.2 Benthic assemblage characterisation**

241 Overall, 80 taxa were identified from 44010 specimens of macrofaunal invertebrates analysed, belonging to phyla
242 Mollusca, Arthropoda, Echinodermata, Nemertea, Platyhelminthes, Phoronida and Annelida, with annelid
243 polychaetes being the richest group (34 taxa). In terms of abundance, molluscs were the dominant macrobenthic
244 group in all locations, constituting 96% - 98% of the entire macrobenthic fauna, followed by polychaetes in
245 northern locations and crustaceans in southern and impacted locations. Assemblages at the impacted location were
246 characterised by significantly lower abundance (pseudo F = 26.973; $P = 0.0143$) and species richness (pseudo F =
247 11.265; $P = 0.0448$) and higher Hill's evenness index (pseudo F = 422.500; $P = 0.0003$) compared to controls (Fig.
248 8). Hill's species diversity index did not show clear differences between impacted and control assemblages (pseudo
249 F = 0.4603; $P = 0.5506$). Assemblages structures at the impacted location were significantly different (pseudo F =
250 31.590; $P = 0.0001$) and more variable compared to those at the control ones (Fig. 9). According to the results of
251 SIMPER analysis (see Table A, part A, in supplementary material), species that mostly characterised benthic
252 assemblages of both control and impact locations were three bivalves, *Lentidium mediterraneum* (O. G. Costa,
253 1830), *Donax semistriatus* (Poli, 1795) and *Chamelea gallina* (Linnaeus, 1758). The relatively high dissimilarity
254 (64.53%) in species composition and abundance between impact and control was mainly due to a drastic decrease

255 in abundance of the same three bivalves in the impacted locations, and to a lesser extent due to lower species
256 diversity in the impacted location (see Table A, part B, in supplementary material).

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

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

279

280 **3.2 Field test results**

281 In the real environment, the ejectors showed similar performances to the ones achieved in the laboratory. The tests
282 therefore allowed to select the ejector able to guarantee the best performances in the most critical conditions, which
283 correspond to the worst sea weather conditions, i.e. sea storms with North-East waves direction. On the basis of
284 previous experience (Bianchini et al. 2014), a mean sand flowrate of about 2 m³h⁻¹ in the discharge flowrate for

285 each ejector is required in critical conditions to balance the sand transported by the waves. Results and figures
286 cannot be shown in detail due to restrictions based on the intellectual properties of the technology.

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

297

298 **3.3 Demo plant design**

299 *3.3.1 Analysis of past bathymetries*

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

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

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

324 On the basis of ejector characteristics and preliminary tests results and sediment characterisation, 10 ejectors are
325 needed to cover such an area, which measures about 1,600 m². Based on historic bathymetry analysis, a mean
326 yearly sediment rate of 3,000-4,000 m³ of sand can be expected in that area.

327

328 ***3.3.2 Demo plant design and installation***

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

338

339 ARPAE stated through a written technical opinion that the actions exerted on the seabed by the demo plant comply
340 with the definition of “*remodelling*” stated in DM 173/2016. Hence, they are not regarded as dredging actions but,
341 rather, as sediment management operations within the same water basin. Therefore, according to Italian law, the
342 demo plant does not need any “dredging-like” authorisation or permit. Furthermore, ARPAE also provided a
343 written technical opinion regarding the discharge points of the demo plant, that are i) water jets out of the ejector
344 central nozzle, ii) water-sediment mixture flowrate out of the ejector discharge pipeline and iii) filter discharge

345 pipeline of the water pumping station. ARPAE stated that all these discharge points cannot be classified as
346 “wastewater discharge” due to the operation mode of the demo plant.

347

348 **4 Conclusions**

349 The MARINAPLAN PLUS LIFE project aims to demonstrate the effectiveness of a novel sediment by-passing
350 plant to be installed at the Cervia harbour inlet. The project, started in October 2016, is now entering the decisive
351 phase, since the demo plant is under commissioning. Nevertheless, many activities have already been completed,
352 including the preliminary testing (in the laboratory and in the field) of the ejectors, the completion of the
353 authorisation/permit procedures, the characterisation of the sediment to be moved and of the existing flora and
354 fauna. The preliminary test results showed that one ejector should guarantee a sediment removal capacity of about
355 $2\text{m}^3\text{h}^{-1}$ with a power consumption of about 3.5 kW, with an area of influence up to 5-7 m in 15 days of operation.
356 The technology has been recognized as not comparable with dredging, meaning that the authorization procedure
357 for the plant installation does not have to comply with dredging legislation (i.e. Italian Law Decree 172/2016).
358 Furthermore, the environmental assessment in the study area showed how the benthic fauna has been greatly
359 negatively affected by the dredging operations that have been carried out over the years at the port inlet.

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

371

372 **Acknowledgements** The research activity was funded by the European Union through the LIFE Programme funds,
373 “Marinaplan plus” Project Life15 ENV/IT/000391.

374

375 **References**

- 376 Amati G, Saccani C (2005) Experimental plant for sediment management in harbours' areas (in Italian). In:
377 Proceedings of the XXXII National Conference on Italian Plant Engineering, 6-7 October, Rimini, Italy
- 378 Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. *Aust J Ecol* 26:32–46
- 379 Anderson MJ, Gorley RN, Clarke KR (2008) PERMANOVA+ for PRIMER: Guide to Software and Statistical
380 Methods. PRIMER-E, Plymouth, UK
- 381 ARPAE (2016) Status of the Emilia-Romagna coast at 2012 - Erosion and defense interventions (Stato del litorale
382 Emiliano-romagnolo al 2012 – Erosione e interventi di difesa, in Italian).
- 383 Bertasi F, Colangelo MA, Abbiati M, Ceccherelli VU (2007) Effects of an artificial protection structure on the
384 sandy shore macrofaunal community: the special case of Lido di Dante (Northern Adriatic Sea).
385 *Hydrobiologia* 586:277–290
- 386 Bianchini A, Pellegrini M, Saccani C (2014) Zero environmental impact plant for seabed maintenance. In:
387 Proceedings of the International Symposium on Sediment Management I2SM, 17-19 September, Ferrara,
388 Italy
- 389 Bianchini A, Cento F, Guzzini A, Pellegrini M, Saccani C (2019) Sediment management in coastal infrastructures:
390 techno-economic and environmental impact assessment of alternative technologies to dredging. *J Environ*
391 *Manage* 248:109332. <https://doi.org/10.1016/j.jenvman.2019.109332>
- 392 Bonsdorff E (1983) Recovery potential of macrozoobenthos from dredging in shallow brackish waters. *Oceanol*
393 *Acta* 4:27–32
- 394 Boswood PK, Murray RJ (2001) World-wide sand by-passing systems: data report. Conservation technical report
395 n°20, Environmental Protection Agency, Queensland Government
- 396 Bray RN, Bates AD, Land JM (1996) *Dredging: A Handbook for Engineers*. Butterworth-Heinemann, Oxford
- 397 Bruun P (1996) Navigation and sand bypassing at inlets: technical management and cost analysis. *J Coastal Res*
398 23:1139-119
- 399 Clarke KR (1993) Nonparametric multivariate analyses of changes in community structure. *Aust J Ecol* 18:17–
400 143
- 401 Clarke KR, Gorley RN (2006) *PRIMER v6: User Manual/Tutorial*. Plymouth: PRIMER-E. 192 pp
- 402 Cooper KM, Curtis M, Wan Hussin WMR, Barrio Froján CRS, Defew EC, Nye V, Paterson DM (2011)
403 Implications of dredging induced changes in sediment particle size composition for the structure and function
404 of marine benthic macrofaunal communities. *Mar Pollut Bull* 62:2087–2094

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

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

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

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

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

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

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

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

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

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

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

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

430 Occhipinti-Ambrogi A, Savini D, Forni G (2005) Macrobenthos community structural changes off Cesenatico
431 coast (Emilia Romagna, Northern Adriatic), a six-year monitoring programme. *Sci Total Environ* 353:317–
432 328

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

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

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

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

443 Schaanning MT, Harman C, Staalstrøm A (2011) Release of dissolved trace metals and organic contaminants
444 during deep water disposal of contaminated sediments from Oslo harbour, Norway. *J Soils Sediments*
445 11:1477-1489. <https://doi.org/10.1007/s11368-011-0436-2>

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

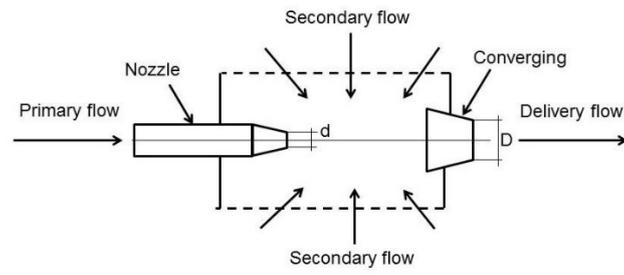
448 Simboura N, Zenetos A (2002) Benthic indicators to use in Ecological Quality classification of Mediterranean.
449 *Mediterr Mar Sci* 3/2:77–111

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

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

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

458



459

460

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

461

462



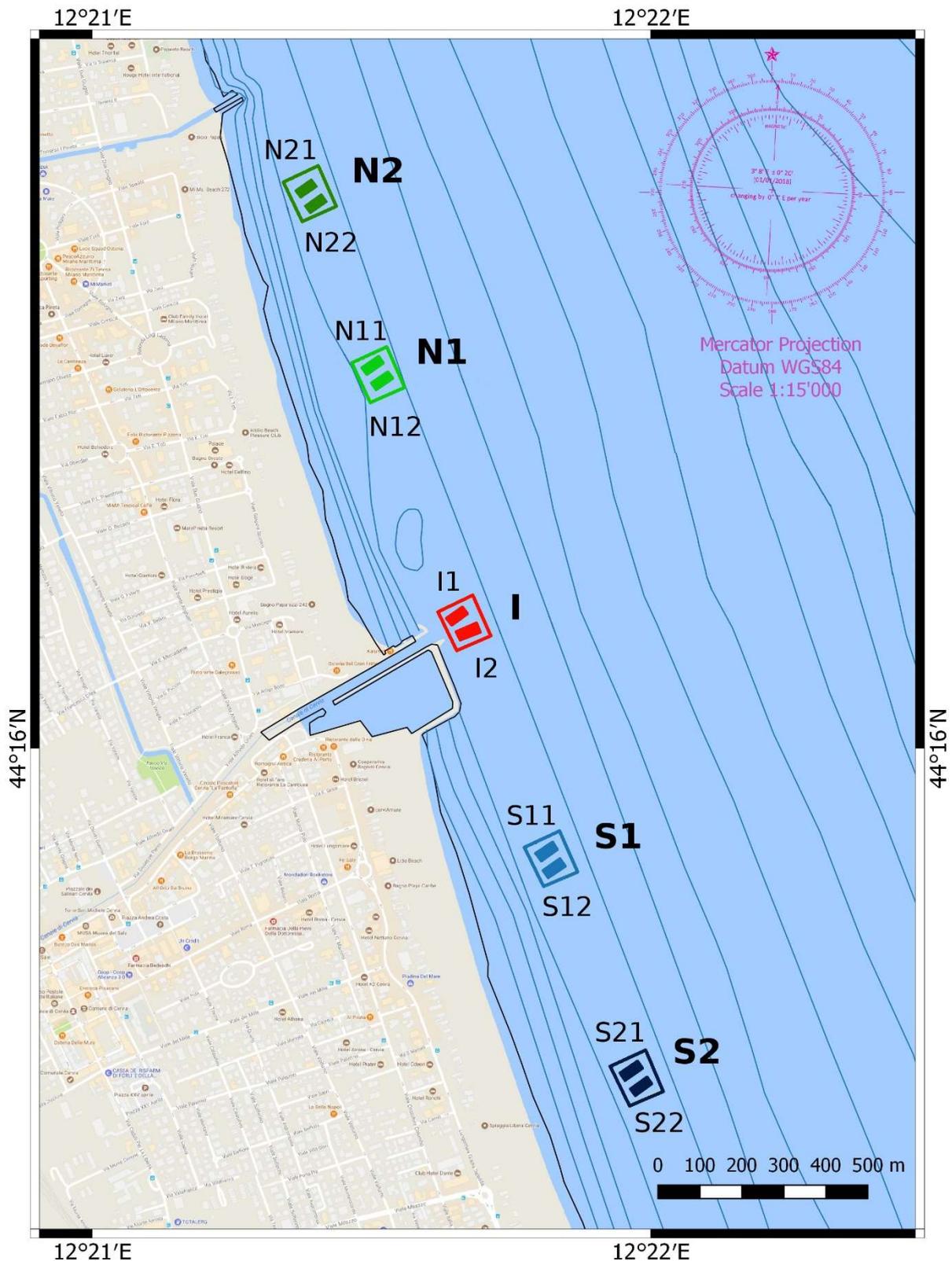
463



464

465

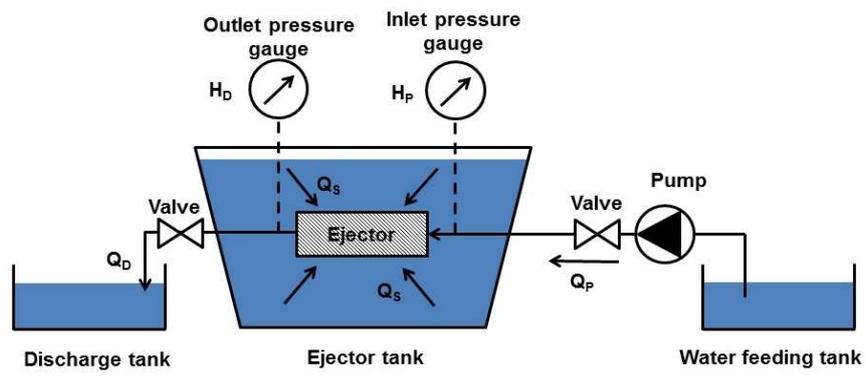
Figure 2. Cervia position and harbour aerial picture of the study area.



466

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

472



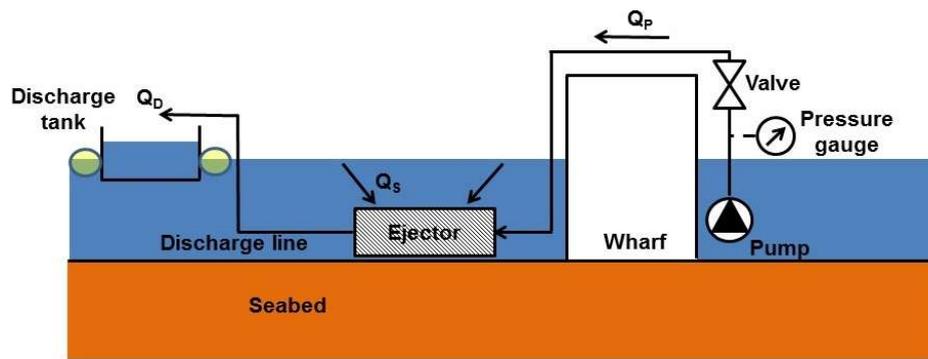
473

474

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

475

476

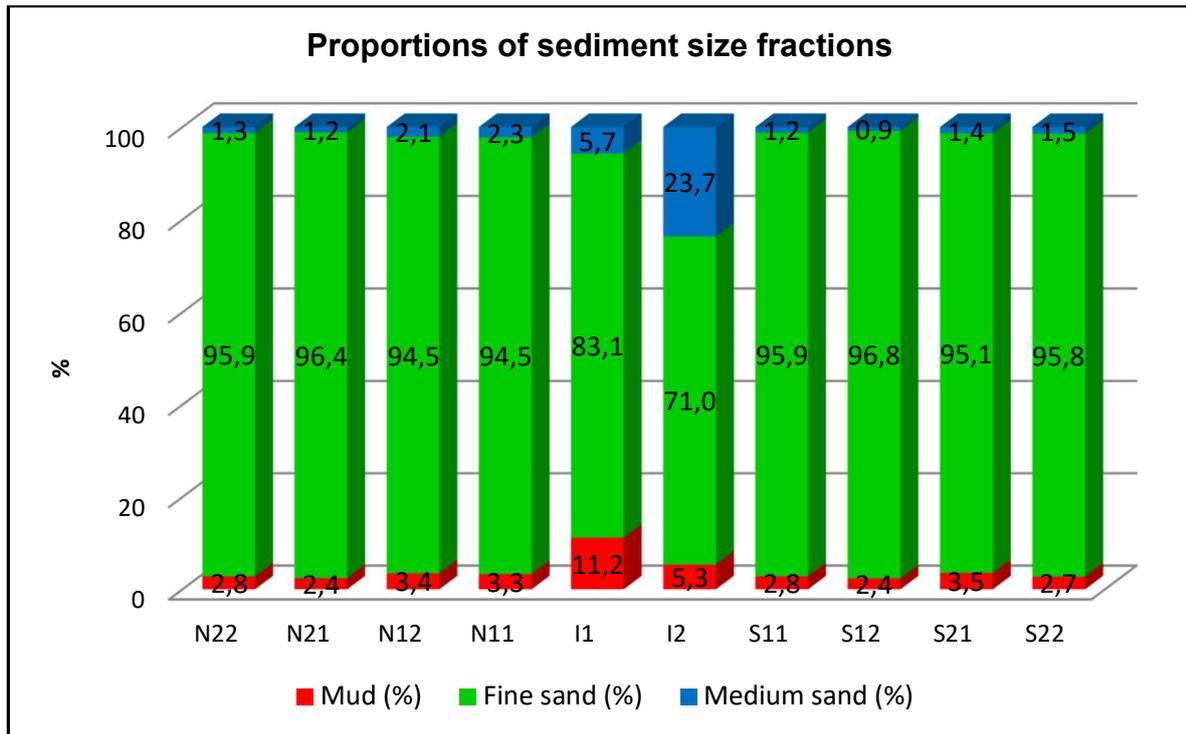


477

478

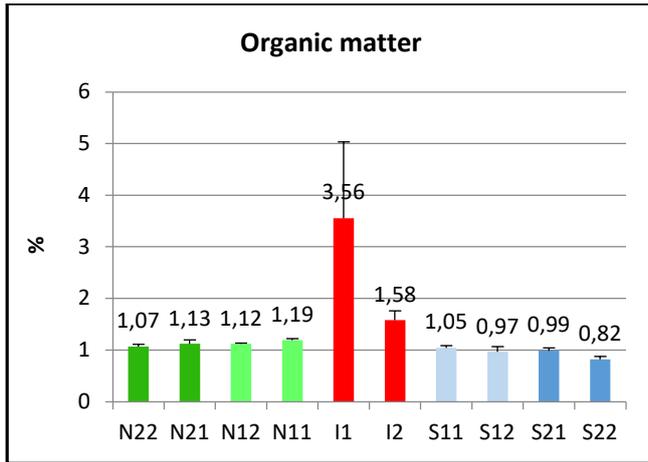
Figure 5. Field testing equipment for ejectors

479

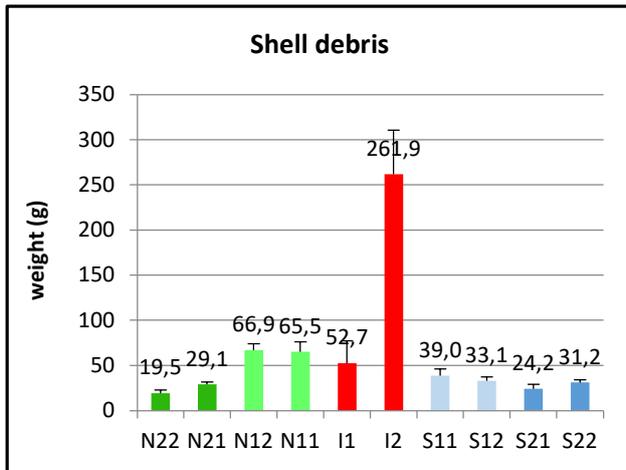


481

482 Figure 6. Mean percentage of sediment size fractions in each research area. N11 and N12 = areas within North
 483 600 m, N21 and N22 = areas within North 1200 m, S11 and S12 = areas within South 600 m, S21 and S22 = areas
 484 within South 1200 m, I1 and I2 = areas within impact



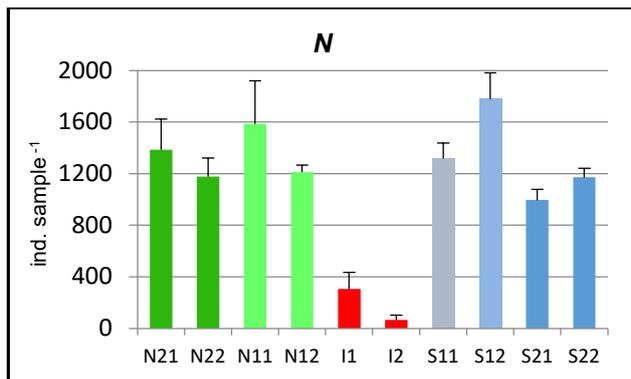
485



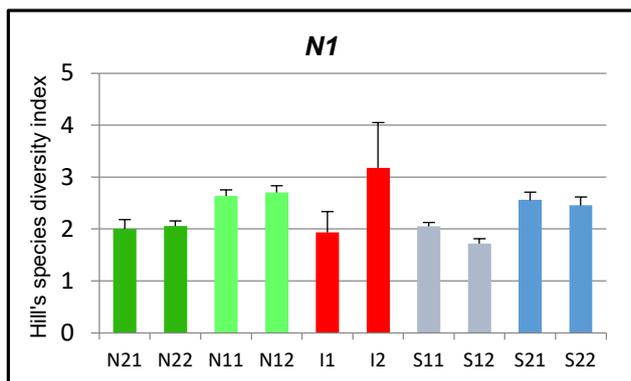
486

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

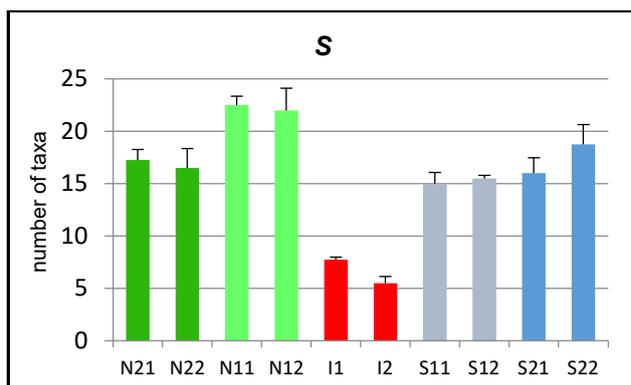
490



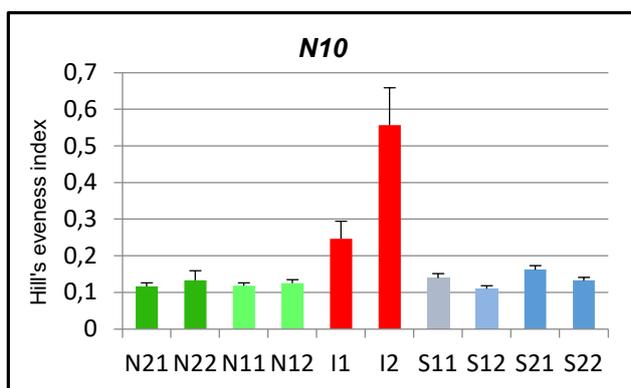
491



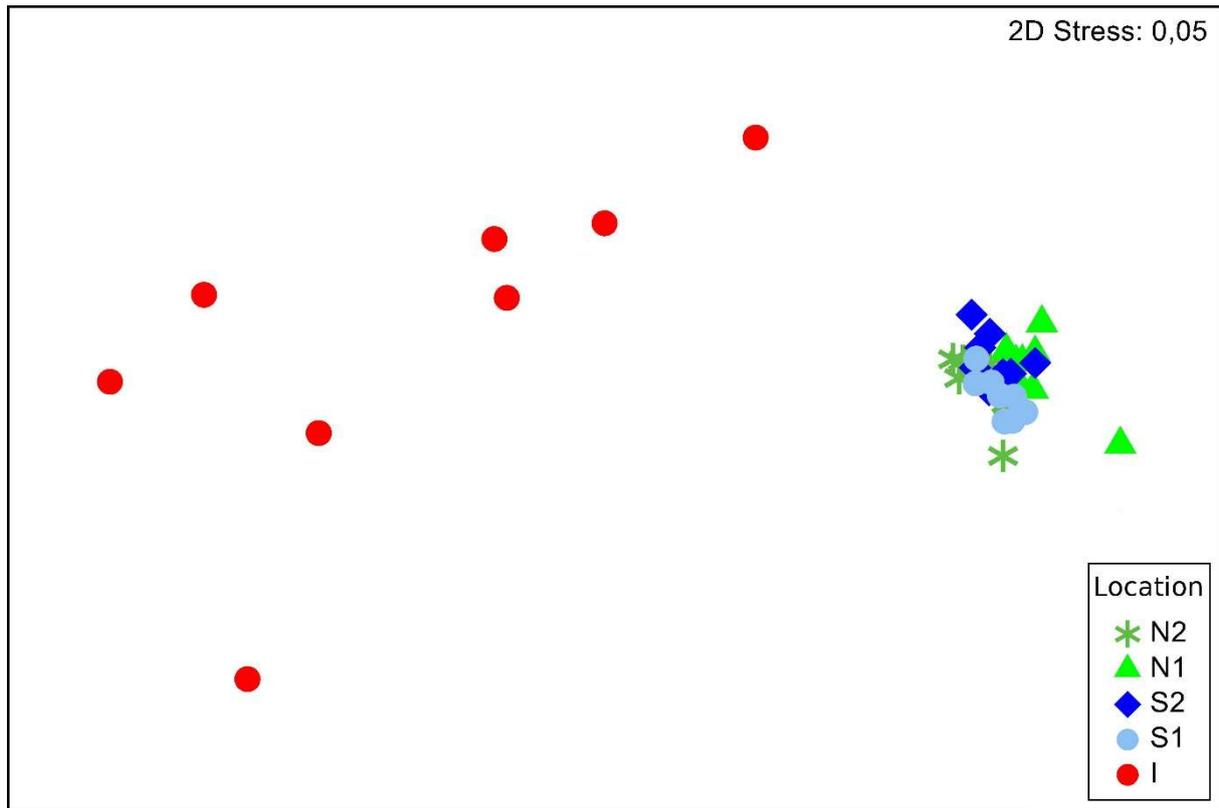
492



493



494 Figure 8. Mean (\pm standard error) total abundance (N), species richness (S), Hill's species diversity index (N1)
 495 and Hill's evenness index (N10) at each research area. N11 and N12 = areas within North 600 m, N21 and N22 =
 496 areas within North 1200 m, S11 and S12 = areas within South 600 m, S21 and S22 = areas within South 1200 m,
 497 I1 and I2 = areas within impact
 498



500

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

504

505 **Table 1.** Dredging and/or sediment handling through boat propellers or dredgers in Cervia harbour from 2009 to
 506 2015.

Year	Month	Operation	Quantity (m³)	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

507