



Techno-economic assessment of the innovative ejectors plant technology for sediment management in harbours

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Abstract

Purpose The paper aims to show the monitoring results of an innovative technology, the ejectors plant, tested in the MARINAPLAN PLUS LIFE project framework for sustainable sediment management in harbours.

Materials and methods A monitoring plan has been designed to evaluate the technical, economic and environmental impact of the ejectors plant demonstrator for 15 months, located in Cervia (Italy). In particular, the demonstrator's effectiveness and efficiency have been assessed to determine the yearly operation and maintenance costs.

Results and discussion The techno-economic analysis shows promising results in terms of efficacy and efficiency of the ejectors plant. The ejectors plant guaranteed navigability for the whole period of operation with a yearly cost reduction compared with traditional dredging.

Conclusions The innovative technology promoted by the MARINAPLAN PLUS LIFE project is a promising solution to manage sedimentation in harbours through a cost-effective and a low environmental impact technology. The monitoring actions validated the technology fully and demonstrated its efficacy and sustainability, highlighting the further improvements needed.

Keywords Sediment management · Harbour · Sediment by-passing system · Operation and maintenance costs

1 Introduction

More than 90% of global trade is carried by waterborne transport, constituting the most important means of transportation of goods. Therefore, international trade is critically dependent on adequate ports, harbours and waterways navigation status (navigability). The vast majority of the 10000 s of ports and harbours worldwide suffer from sedimentation (PIANC 2015). Therefore, preservation of good navigability is a challenging issue, since port and harbour access and waterways are often hampered. Traditionally, the sediment that causes the problem is excavated, removed and relocated through maintenance dredging (Bray et al. 1996). Nevertheless, dredging is not effective in keeping navigability

over time. This objective may be reached through a higher frequency of dredging operations, but it is likely to result in higher costs and complex authorization and permit procedures. Maintenance dredging also has considerable environmental impacts (Bianchini et al. 2019), since dredging operations (i) can destroy or significantly modify underwater habitats and resident flora and fauna (Ohimain et al. 2004; Suedel et al. 2012; Manap and Voulvoulis 2015; Ragnarsson et al. 2015); (ii) can resuspend sediments and contaminants already present in the seabed, thus increasing the Suspended Solid Concentration (SSC) in the water column with adverse effects for the ecosystem (Torres et al. 2009; Schaanning et al. 2011); (iii) can impact locally on greenhouse gas (GHG), pollutants and noise emissions; and (iv) may generate a waste to be disposed of depending on sediment characteristics and national legislation. There is an increasing expectation for infrastructure projects to add value beyond the economic dimension since sustainability issues are of growing importance.

The “ejectors plant” technology has been developed as a sustainable alternative to maintenance dredging and tested by Trevi SpA and University of Bologna in the first demo application in the Marina di Cervia (Italy). The ejectors

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plant can be classified as a sediment by-passing plant. The core of a sediment by-passing plant is the jet pump, a well-known and reliable technology that has several applications in different fields (Stewart 2019). The ejector differs from traditional jet pumps since it can be defined as an open jet pump (i.e. without a closed suction chamber and mixing throat) with a converging section instead of a diffuser and a series of nozzles positioned circularly around the ejector (Fig. 1). The ejector is placed on the seabed and transfers momentum from the central nozzle—a high-speed primary water jet flow—to a secondary flow mixture of water and the surrounding sediment. The surrounding sediment is pre-mixed and prepared for conveying by the circular nozzles of the ejector. The sediment–water mix is then transferred through a pipeline and discharged in an area where the sediment can be picked up again from the natural water current or is not an obstacle for navigation. A full detailed description of the technology and the demo ejectors plant can be found in Pellegrini et al. (2020a). The comparison between traditional dredging and sediment by-passing plant is widely addressed in Bianchini et al. (2019). EASME supported the design, building, operation and monitoring activities in the framework of LIFE MARINAPLAN PLUS project. The ejectors plant operated from June 2019 to September 2020 with the final aim of keeping water depth at the Marina entrance over 2.5 m. During the 15 months of operation, the ejectors plant has been monitored to assess: (i) water depth variation; (ii) energy consumption; (iii) maintenance costs; (iv) seabed features and species diversity; (v) equivalent CO₂ emissions through LCA; and (vi) underwater noise impact. Literature data already demonstrated that sediment by-passing plants can be more economical than dredging (Bruun 1996; Boswood and Murray 2001; Dean and Dalrymple 2004), but operation and maintenance costs are usually based on estimation more than actual data. The paper aims to cover the literature gap by presenting the detailed final results of the monitoring activities on the Cervia ejectors plant, focusing on techno-economic evaluation and comparison with traditional dredging. Preliminary results of the environmental monitoring have been already presented (Pellegrini et al. 2021a). First of all, species richness of marine macro-invertebrates initially reduced in the

impacted area near the harbour as a result of previously repeated dredging (Pellegrini et al. 2020a), and significantly increased 8 months after the ejectors plant began operation (i.e. February 2020), although it remained below the average for control sites. These results suggest an improvement in the ecological status of the marine ecosystem in the area affected by the plant within less than 1 year from the start of plant operation. The impact on underwater noise has been assessed accordingly to Robinson et al. (2014). From analysis, it was shown that in the harbour environment the impact of ejectors and hydraulic pumps to underwater noise level is insignificant. Moreover, ejectors plant technology should also reduce local greenhouse gas (GHG) and pollutant emissions related to dredging operation, especially if the ejectors plant is fed by renewable energy. Final results about environmental monitoring, including a life cycle assessment, will be published in forthcoming papers.

2 Materials and methods

2.1 Cervia ejectors plant description

The ejectors plant installed in Cervia has the main objective of guaranteeing navigability at the harbour inlet while in operation. The Cervia ejectors plant consists of 10 ejectors located at the harbour entrance, as shown in Fig. 2, with in-flow and out-flow pipelines laying on the seabed, delivering the mixture discharge composed of the moved sediments and water in a location south of the harbour entrance channel.

The ejectors plant includes a fully automated and remotely accessible pumping station equipped with auto-purging filters. The pumping station continuously feeds the ejectors with pressurized water. Two submersible pumps are installed in the Marina, each providing water to 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 threshold. An inverter controls the total pumped water flow rate, while electrovalves balance the flow rate for each ejector feeding pipeline. The total installed power is about 80 kW. Water pressure and flow rate

Fig. 1 The ejector: conceptual diagram (left) and photo of it in operation (right)

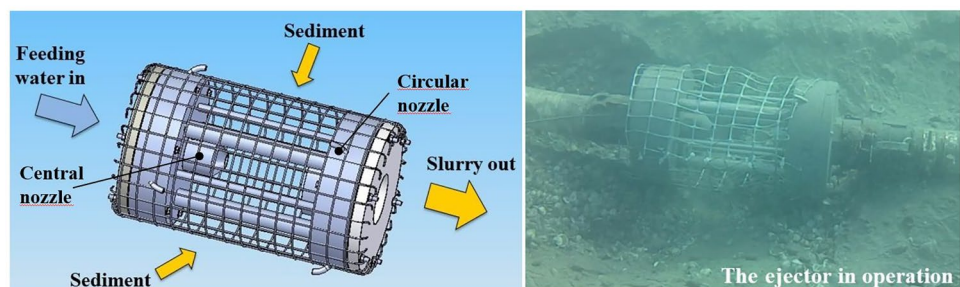
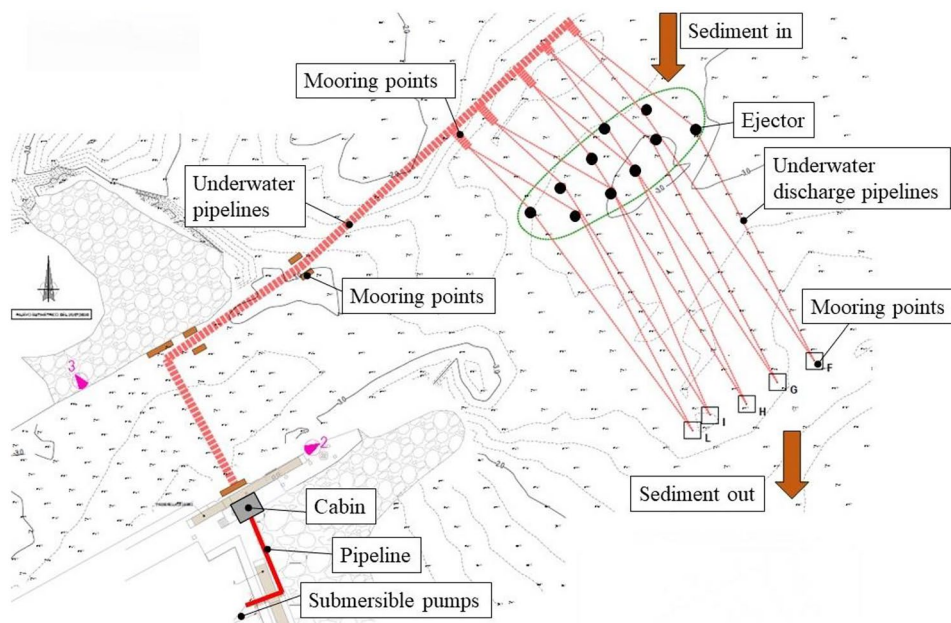


Fig. 2 Location of the 10 ejectors in Cervia plant (Pellegrini et al. 2021b)



and pumps power consumption are continuously monitored, and data are recorded in a cloud server every 5 s.

Cervia’s ejector plant was operated continuously from June 2019 to September 2020, thus achieving the objective of the LIFE MARINAPLAN PLUS project—namely, the monitoring of performance and impacts produced for a minimum period of operation of 15 months. Figure 3 summarizes the five operating phases in which the ejectors plant operation can be divided. In nominal working conditions, each ejector can produce a peak sediment flow rate at the discharge pipeline of about 2 m³ h⁻¹ (Pellegrini et al. 2020a), which corresponds to the 100% load operation. In the first and second phases, the ejectors plant was operated with a reduced load (estimated at 25% and 50%, respectively) and manual control. The strategy was necessary to limit pressure and power consumption since some devices (i.e. underwater pipelines and fittings) showed a lower pressure rating than the one declared by the suppliers. After replacing the non-compliant devices, the ejectors plant entered the third and fourth phases of operation, in which the full load of the ejectors plant was reached. Nevertheless, a growing issue

related to mussels (*Mytilus galloprovincialis*) fouling in the pipes and filters has been detected in the same periods. The ejectors’ performance was highly affected by fouling: as a consequence, a reduced water flow rate was available for the ejectors, and a higher pressure was needed due to the increasing pressure drop, thus dramatically increasing pumps’ power consumption. This is why only two ejectors were in operation in the fifth phase, as shown in Fig. 3.

2.2 Energy consumption monitoring

Data regarding water flow rate and pressure, plus power consumption, are registered every 5 s in a cloud server and are downloadable in *.csv format. Water flow rate is measured in each ejector water feeding pipeline through Endress-Hausser magnetic flowmeters Promag. Pressure is measured by Wika relative pressure transmitter S-20. Power consumption on the electric panel (including pumps, cabin fan and other ancillaries) is measured by the multifunction meter IME Nemo 96 HD.

Demo plant operation regime	2019							2020								
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Phase 1 - Manual, partial load (25% of maximum)	Yellow	Yellow	Yellow	Yellow	Yellow											
Phase 2 - Manual, partial load (50% of maximum)						Green	Green	Green	Green							
Phase 3 - Manual, full load									Yellow	Yellow	Yellow	Yellow				
Phase 4 - Automatic -10 ejectors													Red	Red		
Phase 5 - Automatic - 2 ejectors															Blue	Blue

Fig. 3 Classification by phases of the ejectors plant operation in Cervia

2.3 Bathymetric surveys

The analysis was carried out over 3 years, starting from June 2017 and ending in June 2020, to investigate, for similar loadings in terms of wave climate and seasons, the sediment transport at the harbour entrance: (i) with propeller operation and dredging (2017–2019) and (ii) during the operation of ejectors plant (2019–2020). The chosen periods are characterized by similar wave climates, as shown in (Pellegrini et al. 2021b). All the bathymetries collected have been commissioned by the Municipality of Cervia. They have been carried out through a digital hydrographic ultrasound system (Hydro-trac model, manufactured by Odom Hydrographic Systems, Baton Rouge, LA, USA) with a narrow emission cone, with the resulting error estimated as not exceeding 3 cm. The water depths reference is the mean water level. The bathymetries provided by the Municipality of Cervia include water depth measurements and the related coordination in AutoCAD files. A methodology applying both QGIS 3.14 built-in Python and TIN interpolation was developed to analyse the data (see the detailed description of the method in Pellegrini et al. 2021b).

2.4 Maintenance activity monitoring

Ordinary maintenance activities of the ejectors plant are mainly related to pumps and auto-purging filters cleaning. While auto-purging cleaning operations can be realized on site, the cleaning of the suction filters of the submersible pumps needs the support of a diver. Ordinary and extraordinary maintenance of underwater installation (i.e. ejectors, water feeding pipelines and discharge pipelines connection to mooring points) is complex and requires at least three people team. The maintenance team includes a diver, a boat, one person managing the boat and one person on the ground to coordinate activities, control ejectors plant operation and guarantee safe operation. All the activities carried out on the ejectors plant have been manually registered on a *.doc text file. The registered information includes the duration of the maintenance (start and end time), people involved, used means, activities carried out, spare parts or materials used.

3 Results and discussion

3.1 Ejectors plant effectiveness

From January to April 2019, the last dredging and propeller operation were undertaken before ejectors plant installation. On 13 June 2019 the ejectors plant was activated. The bathymetry determined on 12 June 2019 is the reference bathymetry to evaluate the ejectors plant effectiveness on keeping a sufficient water level at the harbour entrance. The

minimum water depth at the harbour entrance to guarantee navigability was 2.5 m. Under this level, fisherman and leisure boats that use the Marina di Cervia usually start having navigability issues. Figure 4 has been realized based on bathymetries from June 2019 to April 2020 (Pellegrini et al. 2021b) and shows if and where the minimum water depth was reached in the common area at the harbour inlet.

The first relevant result is that at the end of the monitoring period (end of April 2020), a navigable channel is still present (i.e. water depth over 2.5 m) to guarantee safe access to the harbour of Cervia. It is interesting to note how in January 2020 the situation appeared critical in the area of influence of the ejectors, and that this critical situation negatively evolved from September 2019. Nevertheless, it should be considered that until February 2020, the ejectors plant was not able to operate at full load. While starting from February 2020, the technical issues that limited the operation of the ejectors plant were solved thanks to the substitution of underwater fittings and of the electric cables feeding the demonstrator. The maximum impact of the ejectors plant on keeping the water depth at the desired level was observed in the period January–April 2020, wherein the ejectors plant was able to operate at the design water feeding flow rates and with an estimated by-passed sediment volume of between 245 and 750 m³ (Pellegrini et al. 2021b).

3.2 Ejectors plant efficiency

By comparing the energy consumption registered by the general electrical panel of the Municipality (in which the fiscal power metering is installed) and the one in the ejectors plant electric panel, it was possible to observe how a power loss of about 25% was present. The cause was found in the sections of the connection cables between the general electric panel and the technical cabin panel of the ejectors plant (i.e. approximately 450-m distance), which were relatively small and generated heat dissipation by Joule effect. The cables were substituted in February 2020. Table 1 summarizes the energy consumption (without including Joule effect losses) and related monthly costs registered from June 2019 to April 2020. This period corresponds to the ejectors plant operation in the first, second and third phases. The following phases are not considered since they are not representative of ejectors plant performances due to the specific high power consumption measured as a consequence of mussels fouling and the limited numbers of ejectors in operation after July 2020.

In the first phase of ejectors plant operation (13 June 2019–30 October 2019), without considering the contribution of October 2019 due to the reopening of the construction site for the underwater fittings substitution, the mean power consumption was about 28.7 kW (i.e. 2.87 kW per ejector). The second phase (31 October 2019–12 February

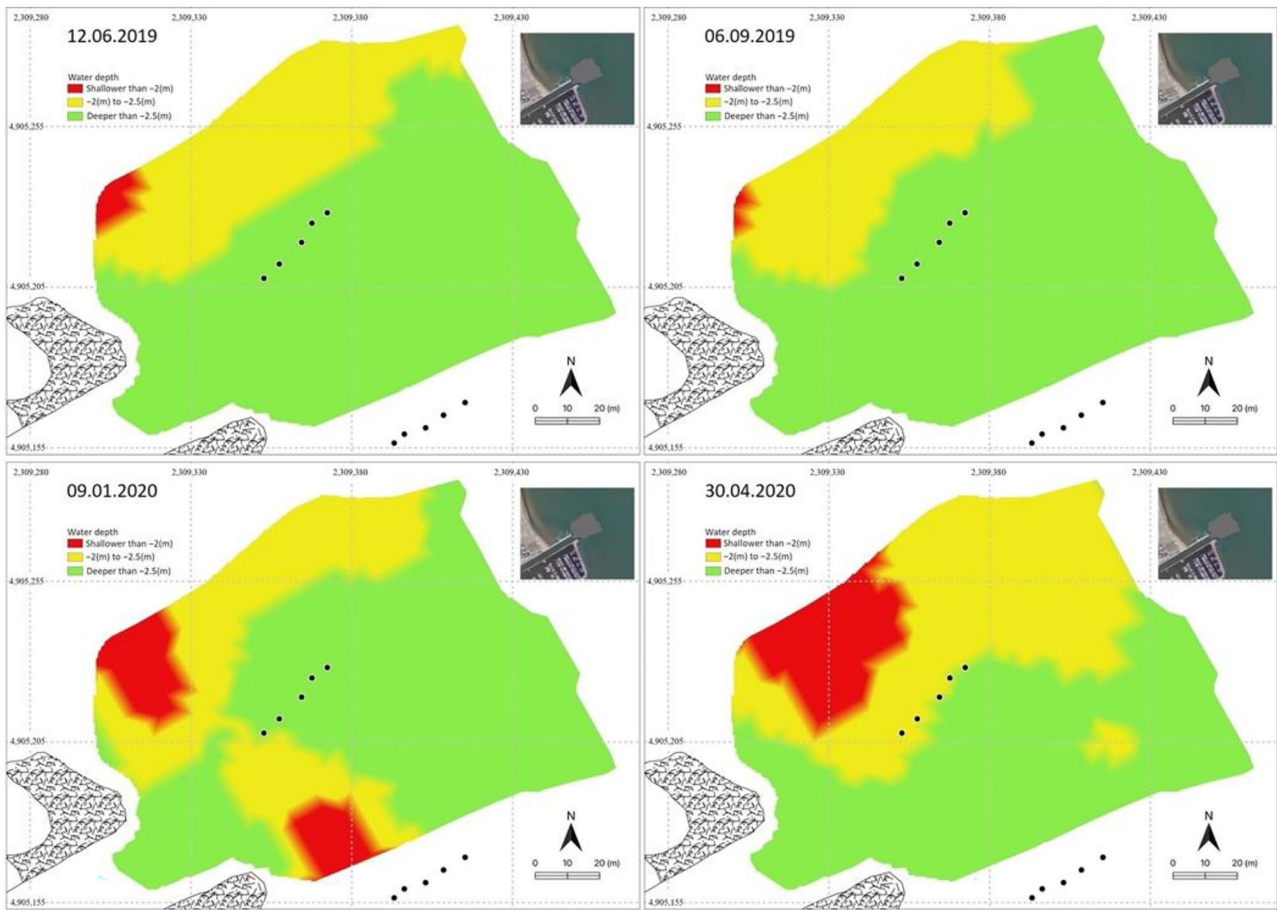


Fig. 4 Critical areas (i.e. water depth <2.5 m) during the ejector operation (12 June 2019–30 April 2020). The positions of the mooring points of the ejectors’ inlet and outlet pipelines are also reported as black dots (Pellegrini et al. 2021b)

2020), with February 2020 not considered due to the change in the control strategy that occurred in the middle of the month, was characterized by mean power consumption of about 52.9 kW. That is relatively less than double consumption compared to the first phase. A further increase in mean power characterized the third phase (12 February 2020–31

May 2020, that is 68.1 kW. May 2020 is not considered due to the reopening of the construction site for the ejectors’ discharge area modifications requested by the Port Authority of Ravenna.

The continuous increase in the period from October 2019 to April 2020 of the power consumption of the ejectors plant

Table 1 Energy consumption and related costs up to the third phase (June 2019–April 2020) without considering Joule effect

Period	Days of operation	Energy (kWh)	Energy per day (kWh/day)	Mean power consumption (kW)	Specific cost (€/kWh)
13/06/2019–30/06/2019	18	12794	711	29.6	0.23
01/07/2019–31/07/2019	31	20106	649	27.0	0.22
01/08/2019–31/08/2019	31	21165	683	28.5	0.21
01/09/2019–30/09/2019	30	21288	710	29.6	0.22
01/10/2019–31/10/2019	31	38421	1239	51.6	0.22
01/11/2019–30/11/2019	30	38309	1277	53.2	0.21
01/12/2019–31/12/2019	31	39043	1259	52.5	0.21
01/01/2020–29/02/2020	60	82569	1376	57.3	0.19
01/03/2020–31/03/2020	31	51795	1671	69.6	0.20
01/04/2020–30/04/2020	30	47912	1597	66.5	0.20

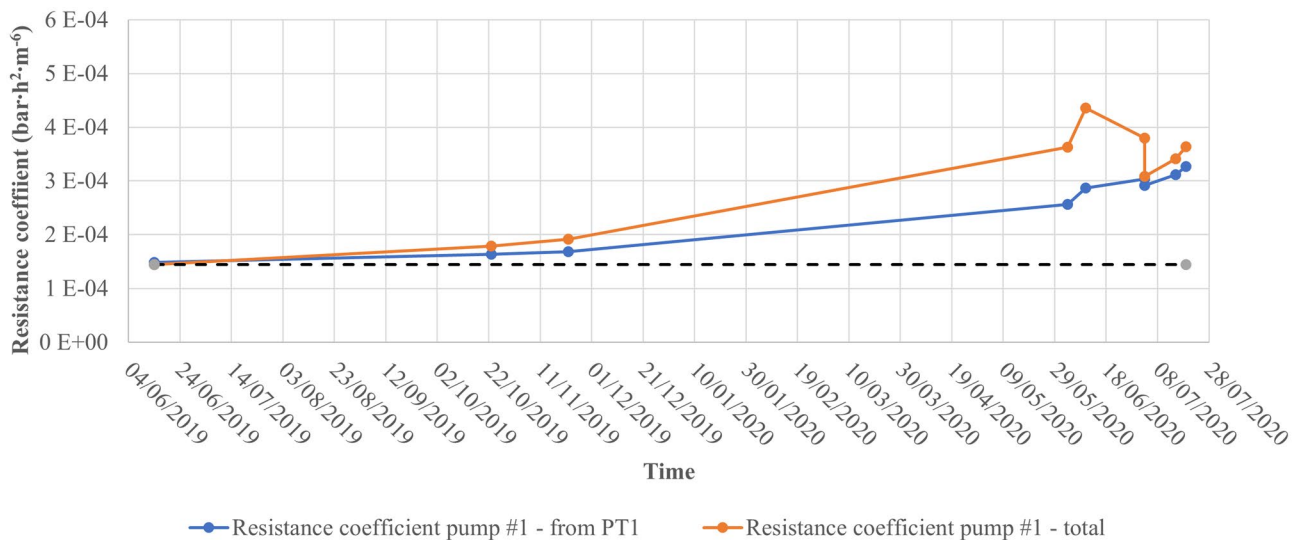


Fig. 5 Variation of the characteristic resistance coefficient of the water feeding lines connected to pump #1 measured from the pressure transmitter (PT1) and estimated from pump outlet

can be mainly attributed to mussels fouling. By following the hypothesis that at the ejectors plant start (June 2019) the mussels fouling was absent or at least not relevant, the characteristic resistance coefficient of the ejectors plant (expressed in pressure divided by squared flow rate, i.e. $\text{bar h}^2 \text{m}^{-6}$) has been drafted in Figs. 5 and 6 based on flow rate and pressure measurements realized by the control system in 14th and 15th June 2019. It is important to note that the pressure is measured inside the technical cabin, i.e. not at the very outlet section of the pumps. This detail will be relevant when assessing ejectors plant power consumption.

The blue curves of both Figs. 5 and 6 are drafted based on the measured values of flow rates and pressure in each line. In contrast, orange curves are estimated based on the comparison between measured flow rate and pump frequency and the expected value of pressure based on the characteristic curve of the pump. For example: on 23rd of October 2019, the measured parameters for pump #1 were $153.2 \text{ m}^3 \text{ h}^{-1}$, 3.84 bar and 2514 rpm, but the expected head of the pump with this water flow rate and pump speed is 4.2 bar. It means a pressure drop (not measured by the pressure transmitter, which is located in the technical cabin) between the

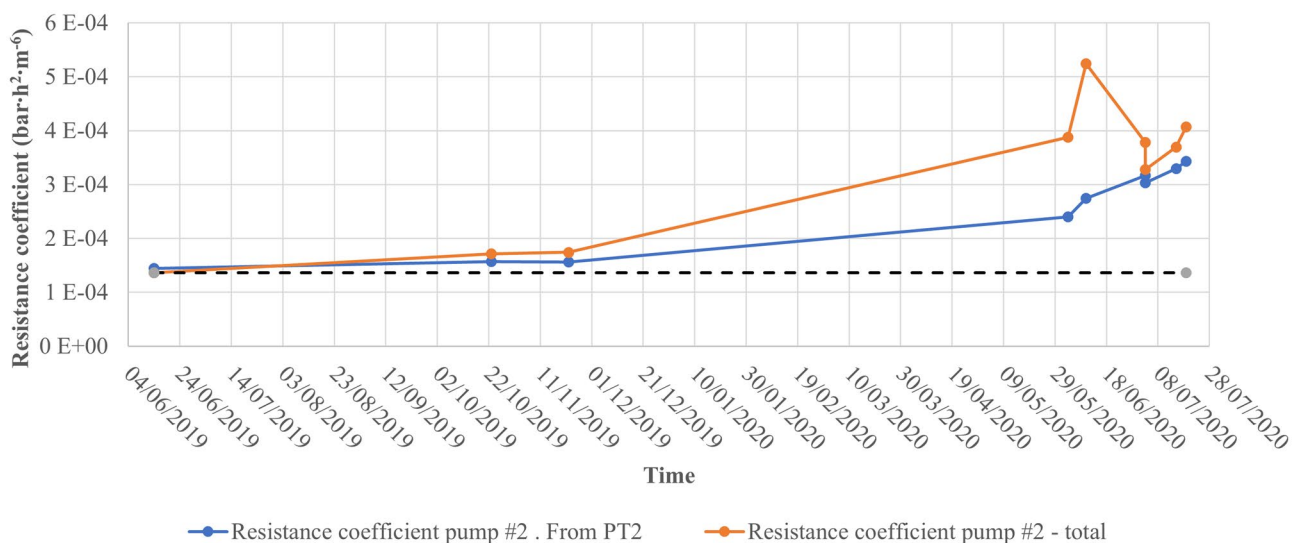


Fig. 6 Variation of the characteristic resistance coefficient of the water feeding lines connected to pump #2 measured from the pressure transmitter (PT2) and estimated from pump outlet

pump and the pressure transmitter itself, which is about 0.3–0.4 bar. The pressure drop is derived from two separated contributions: (i) pumps' filters fouling and (ii) pipeline fouling. The linear variation between November 2019 and June 2020 is an approximation: no comparable data is present in the period since the ejectors plant operated with some pipelines damaged and/or with electrovalves partially or wholly closed, thus affecting the resistance coefficient of the pipelines. The conclusion is that fouling contributed to multiply the resistance coefficient of pipeline of pump #1 and pump #2 of a mean factor of 1.2 and 1.5, respectively, with a peak of up to 2.4 and 2.9 from June 2020.

The ejectors operation should be considered to evaluate the energy consumptions in “normal” conditions, i.e. without fouling issues and no Joule effect. In June 2019, both lines operated with a water flow rate of about $160 \text{ m}^3 \text{ h}^{-1}$ (i.e. $32 \text{ m}^3 \text{ h}^{-1}$ per ejector) with a power consumption of 23.5 kW per pump, or 4.7 kW per ejector. Nevertheless, this water flow rate corresponds to the maximum value to be used in high sediment load transport (Pellegrini et al. 2020a). In flushing conditions, the water flow rate can be reduced to $120 \text{ m}^3 \text{ h}^{-1}$ per pump (or $24 \text{ m}^3 \text{ h}^{-1}$ per ejector), which corresponds to an operating pressure of almost 2 bar and power consumption of about 9.5 kW per pump (less than 2 kW per ejector). The typical mean power consumption of the ejectors plant can be prudentially estimated at 3 kW per ejector. Considering 8,400 h as working hours in a year, it means an energy consumption of about 252,000 kWh year⁻¹ for the 10 ejectors plant.

3.3 Techno-economic evaluation

Table 2 summarizes the costs for ordinary and extraordinary maintenance activities for the whole ejectors plant operation period of 15 months. The activities include (i) maintenance carried out by single diver (including workers) and a team of divers (one diver on water, one diver in stand-by plus one operator and one coordinator, boat included) and (ii) maintenance carried out by workers. The pipelines and fittings substitution activities due to supplying failure are not included.

The whole energy consumption in June 2019–April 2020 has been about 455000 kWh, for a total cost of about 100,000 €. But if power losses due to the Joule effect are not

included, the energy consumption and related costs in the same period would have been 373000 kWh (see Table 1) and 82000 €, respectively. If fouling impact is not considered, a further reduction in energy consumption and costs would be reached: 252000 kWh of energy consumption and about 55000 € of cost. While the Joule effect can be avoided in future installations through a careful design of the electric wirings, the limitation of fouling issues can be addressed by following different approaches. It is worthy to say that fouling issues were not observed in the two last experimental plants at lower technology readiness level in Riccione and Portoverde (Amati and Saccani 2005; Bianchini et al. 2014). But the absence of fouling may be explained by the shorter period of operation (respectively, 6 and 8 months) of the two plants and by a difference in water quality (i.e. availability of nutrients). The more recent application of two ejectors in Cattolica (Pellegrini et al. 2020b) confirms the absence of fouling issues, although the plant has been in operation for consecutive 16 months. Cattolica plant is still running at the time of the preparation of the paper after seasonal and extraordinary maintenance activities. After the fouling issue was observed in Cervia, the Marina manager as well as the local shipyard and sailors was interviewed. They confirmed to LIFE MARINAPLAN PLUS partners that mussels fouling, which is historically present in the area, rocketed inside the Marina (i.e. where the pumps of the ejectors plant were installed) in the last years. A possible explanation is in the modification of the location of fishery boats, including the ones devoted to mussels farming activities, that are now closer to the inner Marina entrance. So, fouling risk must be carefully evaluated in the design phase of future plants. If the risk is assessed as medium or high, the best solution is to integrate the ejectors plant with an anti-fouling system (Cristiani and Perboni 2014; Ge et al. 2019), like environmentally friendly chemicals injection, low-frequency magnetism devices, ultrasonic systems and use of ultrapure copper before or after pumping and filtering stations.

The comparison with yearly traditional maintenance dredging costs is shown in Table 3. Operation and maintenance (O&M) costs of the ejectors plant are computed as the sum of annual maintenance costs and energy bills. The annual maintenance cost is estimated at 16,500 € (= 20600 € × 12 months/15 months), being the costs summarized in

Table 2 Resume of ordinary and extraordinary maintenance costs for the whole period of 15 months

Personnel involved	Quantity	Unitary cost	Cost
Single diver plus two workers	11 days	1000 €/day	11000 €
Divers team	2 days	3500 €/day	7000 €
Two workers	52 h	50 €/h	2600 €
Total			20600 €

Table 3 Comparison between mean yearly cost of maintenance dredging (Pellegrini et al. 2020a) and yearly operation and maintenance (O&M) costs of the ejectors plant

Mean yearly cost of maintenance dredging (€)	O&M yearly cost of the ejectors plant		
	Current	No Joule effect	Optimal
185000	130500	110500	79500

Table 2 distributed over 15 months. Three different values for the yearly energy cost can be assumed: the current costs incurred during the project (114000 €), the costs without considering the Joule effect (94000 €) and the costs by considering the optimal operation of the ejectors plant, i.e. no Joule effect and fouling issues (63000 €). Therefore, also by considering the worst energy consumption scenario, the ejectors plant can produce a saving of 50000 € per year compared to traditional maintenance dredging as paid by the Municipality of Cervia. The economic assessment does not include economic benefits arising from environmental impact reduction of ejectors plant compared to traditional dredging. Positive impacts on biodiversity, underwater noise, GHG and pollutants emissions should be included in the economic evaluation by using monetary valuation of the environmental effects (Amadei et al. 2021). Nevertheless, the review requires the finalization of environmental impacts assessment and the following life cycle assessment analysis and comparison with traditional dredging, which is not in the scope of the present paper.

4 Conclusions

The MARINAPLAN PLUS LIFE project aimed to demonstrate the effectiveness of novel sediment by-passing plant to be installed at the Marina di Cervia harbour inlet. The project, completed in December 2020, allowed extensive monitoring actions, including both techno-economic and environmental assessment. The demonstrative characteristic of the project has allowed highlighting some key points for future design optimization: (i) greater attention in the energy supply design and planning; (ii) realization of pre-test to certify and properly select suppliers of underwater devices, in particular pipelines and fittings; (iii) preliminary assessment of fouling risk and integration of anti-fouling system in the pumping and filtering stations. On the other hand, the ejectors plant guaranteed navigability during the operation period. In particular, the presence of a 2.5-m-depth channel in Cervia at the end of April never happened before without using dredging equipment or propellers operation. The proven effectiveness of the system is accompanied by a yearly O&M cost that is lower than the mean annual cost for traditional maintenance dredging. A direct economic comparison is made difficult by the different operation approaches followed by the two technologies: while dredging removes a measurable volume of sediment in a short time, the ejectors plant continuously guarantees navigability by removing the sediment approaching a certain area. Therefore, the quantity of sediment managed by the ejectors plant can be only estimated. Nevertheless, the economic comparison should also monetize social and environmental benefits generated by the ejectors plant, namely the reduced

impact on the marine environment and the navigability guaranteed all over the year. A following paper will assess how to measure the other economic impacts of the ejectors plant.

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Declarations

Competing interests The authors declare no competing interests.

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