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Application of an Innovative Jet Pump System for the Sediment Management in a Port Channel: Techno-Economic Assessment based on Experimental Measurements

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Abstract: The realization of infrastructures in coastal environment modifies water and sediment natural current regime. In particular, sediment can be entrained and accumulated in port infrastructure like docks, haling basins, or port entrances and channels, creating problems for navigation and limiting the human activities. The result is that marine basins and approaches are frequently silted and require maintenance dredging. Dredging is a consolidated and proven technology which implies relevant drawbacks, like high environmental impact on marine flora and fauna, mobility and diffusion of contaminants, and pollutants already present on the seabed, limitations to navigation, relatively high and low predictable costs. Starting from 2001 an innovative plant for sediment management, alternative to maintenance dredging, has been developed and tested. The core of the plant is the "ejector", an open jet pump fed by pressurized water that is able to suck and convey in a pipeline the sediment that may accumulate in a certain area. On August 2018, a pilot plant has been installed in the haling basin of Cattolica (Italy), as part of a pilot initiative included in the Interreg-Med project "Promoting the co-evolution of human activities and natural systems for the development of sustainable coastal and maritime tourism" (CO-EVOLVE). The aim of the specific experimental activity was to test and monitor the efficacy of the technology applied in a port channel and working with sediments like silt and clay instead of sand. The paper shows the results of the monitoring campaign carried out by the University of Bologna from August 2018 to July 2019.

Keywords: dredging; jet-pump; ejector; blue growth; green port

1. Introduction

Tourism in marine and coastal areas is a complex phenomenon which brings along both positive and negative effects on the environment as a result of activities exerted upon such areas by proponents and tourists. The development of a sustainable marine and coastal tourism is a part of the more general blue growth (BG) long term strategy [1]. The concept of green port (GP), which is defined as a product of the long-term strategy for the sustainable and climate friendly development of port's infrastructure [2] is a fundamental part of the BG strategy and aims to achieve environmental, societal, and economic benefits through resource conservation, waste reduction and pollution prevention in ports areas. While ports and channels efficiency, connectivity, and capacity have always been important topics, the recent years have seen a growing interest in the environmental impact of ports and channels operations and development due to pressing global ecological issues.

Ports and channels navigability is directly connected with marine and coastal tourism development, since the presence of a certain water depth allows the accessibility to the docks of boats with a maximum draft; thus, highly influencing the characteristics of recreational boating as well as touristic or industrial ships that can reach or not a specific destination. In particular, recreational boating is an internationally significant nature-based activity, which is especially popular in the Mediterranean region [3], and provides high economic value since the spin-off work usually promotes and supports local activities like fishing, marine cultivation, shipbuilding, and boat manufacturers [4].

The need to remove the deposited material from the water basins is a common feature shared by many ports and channels, since the earliest settlement along coasts and river [5]. Sedimentation characteristics and causes depend on the intensity of seas and rivers currents, which, thanks to the energy of their movement, carry a large amount of sediment that release due to their interaction with the ports structures [6–8]. Sedimentation dynamic may vary from location to location, but generally affects and limits the navigability and the related activities. Since sedimentation can negatively affect the local development and preservation of recreational boating, the design of a sustainable sediment management in water basins is crucial.

Normally, the most widely used solution to remove sediment deposits is dredging [9]. Dredging is a well-known, reliable, and diffused technology. Nevertheless, in specific conditions (i.e., smaller marinas and channels) dredging in shallow water requires scaled technologies which are less productive and more expensive than standard configuration [10]. Moreover, dredging is only able to restore the desired water depth but without any kind of impact on sedimentation causes. So, dredging cannot guarantee sedimentation avoiding over the time. Moreover, dredging operation, usually interfere with other nautical activities and often implies the prohibition of navigation. Dredging also implies high environmental impacts for the marine ecosystem [11]: dredging operations destroys and strongly modifies marine habitat and can also shuffle contaminants already present in the seabed [12]. Therefore, dredging operations are often becoming too expensive and/or not allowed by normative framework due to the high environmental impact. New approaches have been developed over the years as alternative methods to maintenance dredging; sand by-passing systems with jet pumps seem to be the most suitable solution, since the environmental impact is minimized and investment and operation costs are competitive if compared with dredging cost per cubic meter of sediment handled [9]. Starting in 2001, the University of Bologna and the start-up Plant Engineering Srl developed and tested an innovative device called an "ejector". The ejector 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. In 2005, the first experimental plant [13] was realized and tested in the port of Riccione (Italy). In 2012, a second experimental plant [14,15] was realized in the Portoverde Marina (Italy). The first industrial scale demo is now running in Cervia (Italy), and the activities include a complex monitoring schedule to validate the technology in terms of both economic and environmental impact [16]. All the above mentioned installations have been realized at port entrances and were designed to handle sand.

A valuable opportunity to explore the multiple links among Mediterranean coastal tourism, ecosystem services and the other human activities was provided by the Interreg-Med project "Promoting the co-evolution of human activities and natural systems for the development of sustainable coastal and maritime tourism" (CO-EVOLVE, 2016–2019; https://co-evolve.interreg-med.eu), which aimed at analyzing and promoting the co-evolution of human activities and natural systems in Mediterranean touristic coastal areas [17]. CO-EVOLVE gave the possibility to rapidly share and cross-validate the produced information and frameworks among the seven pilot areas and the 12 partners involved from five EU countries (Spain, France, Italy, Croatia, and Greece) and to benefit from their expert-based assessment. One of the pilot areas of CO-EVOLVE was Cattolica (Italy), in which four laboratories have been set up and worked for over 12 months to redesign the port area through the involvement of different stakeholders (public bodies, universities, citizens and workers associations, private companies). One laboratory was focused on the design of a sustainable sediment management in the port area, which includes the realization of a pilot plant based on the ejector technology. Emilia-Romagna region (CO-EVOLVE project partner) commissioned to the company Trevi SpA the realization of the pilot plant and to the Department of Industrial Engineering of the University of Bologna the monitoring of the pilot plant for the first year of operation.

The novelty of the application lies in the fact that for the first time the ejectors have been applied in the management of silt and clay sediments. The paper describes the pilot plant realized in Cattolica and shows the results of a 12 months monitoring campaign (from August 2018 to July 2019). In particular, the monitoring activities include (i) the impact assessment of the pilot plant on water depth in the installation area, (ii) the evaluation of power consumption, and (iii) the computation of maintenance activities. On the basis of the results, a comparison with dredging operation has been carried out by considering economic concerns.

2. Materials and Methods

2.1. Cattolica Port Area Description

Cattolica municipality is a small touristic town of about 17,000 inhabitants located on the Adriatic coast. The economic activities are mainly related to seaside tourism and marine activities. The port of Cattolica develops along the mouth of the Tavollo stream and is protected by two quays. An important expansion of the port facilities was developed in 2008, building a new marina on the northern perimeter adjacent to that of the 1930s, that now is dedicated only to fisheries, and a new small marina (in the yellow area in Figure 1) surrounded by several services, including industrial and commercial activities, along the Tavollo stream.

Figure 1. Aerial view of Cattolica port area.

In particular, the small marina is located in a redeveloped area which includes a shipyard, one towing basin and one of the production sites of the Ferretti Group, dedicated to the realization of motor yachts between 20 and 30 m length (Figure 2). While the port inlet, the new marina and the old port suffer from sedimentation mainly caused by the sand transported by the sea, the area of the small marina and, more in general, upstream of the old port is affected by sedimentation of silt and clay transported by the Tavollo stream. The towing basin is used by the shipyard for the ordinary and seasonal maintenance operation to be done on private boats and fisheries, but it is also used by Ferretti to launch its yachts, which setting up is finalized in the nearby small marina. So, the accessibility to the towing basin is crucial for the port economy, since it impacts on recreational boating, fishing, and industrial activities. The pilot plant has been installed in the towing basin.

Figure 2. Aerial view of the new small marina area.

2.2. Brief Description of the Ejector Technology

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 [18]. In a sediment by-passing plant, the jet pump is placed on the waterbed 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 water current or where it is not an obstacle for navigation. The technology is reliable since it has been applied starting from the 1970s for coastal application, it requires limited personnel, is extremely portable and can be assembled at reasonable cost.

In the case of Cattolica pilot plant, the main element of the plant, called "ejector" (Figure 3), 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 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 channel at the desired water depth.

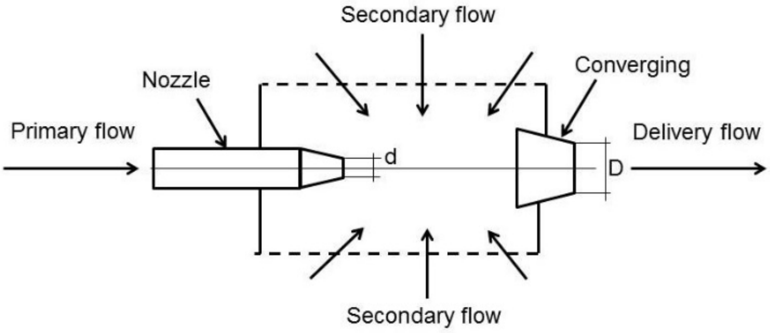

Figure 3. Sketch of the ejector, reproduced from [14].

Ejector design has been optimized 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 [14,15]. Several tests have been carried out both in laboratory and in field to identify the relationships between nozzle diameter d, discharge pipeline length L and secondary flow Q_S. In fact, if it is well known from literature that, in the same boundary condition, the lower is the ejector nozzle diameter d the higher is the suction efficiency Ψ (defined as the ratio between the secondary flow Q_S and the delivery flow Q_D). On the other hand, suction efficiency Ψ must be controlled to avoid discharge clogging risk due to sediment deposition along the pipe [14,16]. The accurate knowledge of ejectors operation in different operating conditions allowed 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. Nevertheless, all the previous tests, including demo plant in Cervia, were realized with sandy sediment. Therefore, different ejector configurations (i.e., diameter d of the central nozzle and number of circular nozzles) need to be tested to identify which ones fit better with the Tavollo sediment characteristics. Table 1 compares sediment characteristics of Cervia and Cattolica.

Table 1. Characteristics of the sediment in each plant installation. Specific weight is measured accordingly to [19].

Sediment Characteristics	Cattolica	Cervia
Specific weight (g/mL)	1.3	1.9
Sand	10.1	97.1
Silt and clay (pelite)	89.9	2.9

2.3. Pilot Plant Description

The pilot plant has been designed to feed with pressurized water up to two ejectors. The Piping and Instrumentation Diagram (P and ID) of the pilot plant is shown in Figure 4. Each ejector is fed by its own submersible pump. The water flowrate in each ejector feeding pipeline can be controlled by inverter. The water pressure at the pumps outlet is monitored by pressure transmitters (PT in Figure 4). Power consumption is measured by an electric multimeter installed between the grid and the inverters. The pumps operation can be scheduled on an hourly base, while the plant operation can be remotely checked and modified. Instruments readings have a frequency of about one second, but data are saved only every five minutes in a local database that can be remotely accessible to limit the size of the data storage.

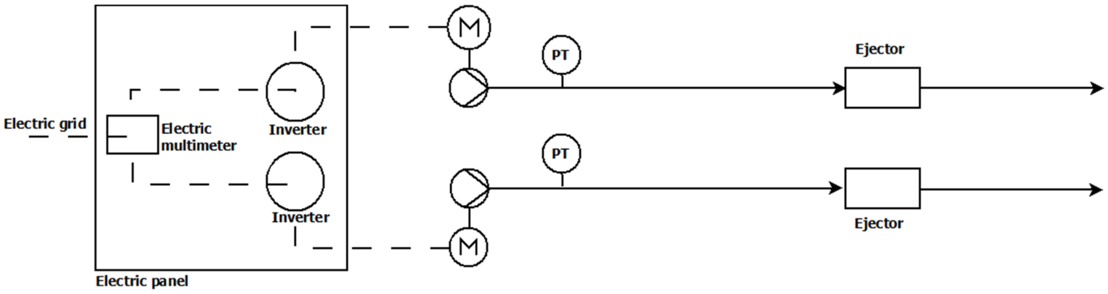

Figure 4. Piping and Instrumentation Diagram (P and ID) of the pilot plant.

Figure 5 shows hot the pumps have been installed. Each pump is horizontal to avoid the contact between the water suction filter and the stream bed. Each pump is about 0.8 m over the stream bed, and it is fixed to the dock through three ropes. Both pumps are submersible pumps with cooling sleeves installed. At the pumps outlet some PVC connections are present. These connections come out from the water to allow the installation of the pressure transmitters. PVC connections have been sized to guarantee a distance of about 0.5 m of the pressure transmitters from the maximum tide. The PVC pipeline ends with a cam-lock connection to which the ejector water feeding pipeline is connected. Both ejector feeding and discharge pipelines have an inner diameter of 0.076 m. The feeding pipeline is made of PE and can work with a pressure up to 8 bar, while the discharge pipeline is made a transparent pipe made by PVC with a metallic spiral, and it is able to operate up to 4 bar.

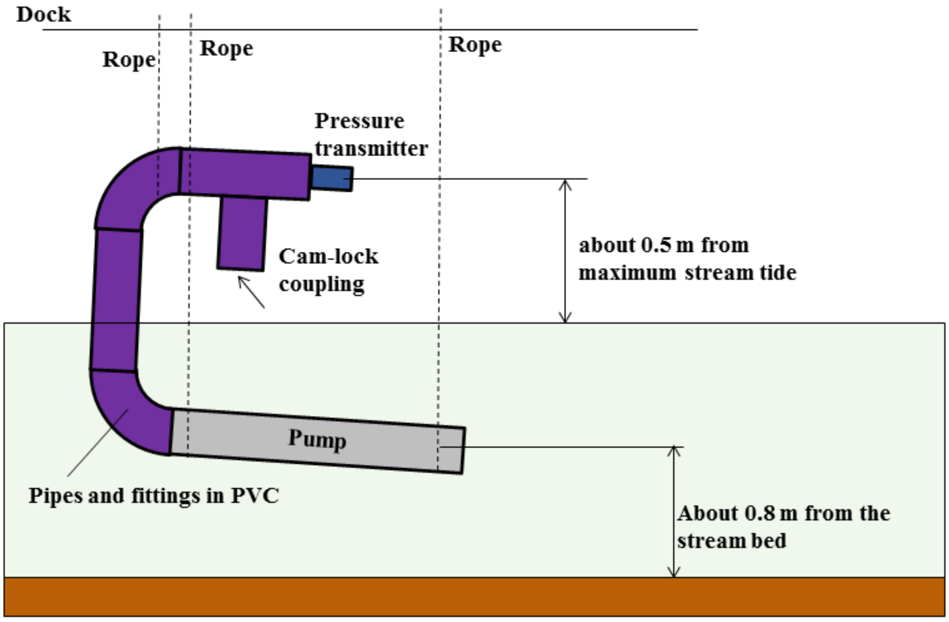

Figure 5. Schematic of pump installation.

The pumps are installed near the entrance of the towing basin, while the ejectors are located inside and outside the towing basin. The internal ejector has been numbered as ejector n°2, while the external ejector is the n°1. The electric panel has been installed very close to the pumps. Figure 6 shows the position of pumps, ejectors, and electric panel. The position of the ejectors is approximate, since they were not fixed on the stream bed and during the 12 months of monitoring the ejectors, and in particular the ejectors n°2, were manually moved. The discharge line of ejector n°1 is 30 m length, while the one of ejector n°2 is 52 m. Both discharge pipelines ends were fixed by ropes to the opposite dock. Table 2 summarizes the characteristics of main devices of the pilot plant.

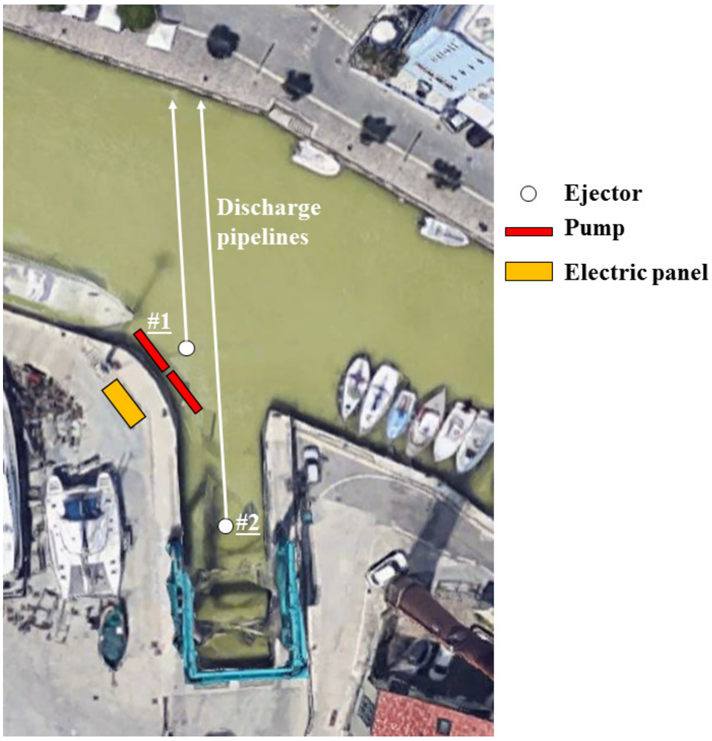

Figure 6. Position of ejectors, pumps and electric panel.

Table 2. Characteristics of the main components of the Cattolica pilot plant.

Devices	Main Characteristics
Pump for Ejector n°1	Submersible pump with cooling sleeve and inverter; manufacturer: Grundfos; model: SP 46-3-C R; sourced from Cesena, Italy.
Pump for Ejector n°2	Submersible pump with cooling sleeve and inverter; manufacturer: Grundfos; model: SP 46-4-C R; sourced from Cesena, Italy.
Water feeding Pipeline	Flexible PVC pipe with a reinforced PVC spire, internal diameter 78 mm, maximum operating pressure 6.5 bar; manufacturer: Sati Trading; sourced from Bologna, Italy.
Discharge Pipeline	Flexible PVC pipe with a metal spire, internal diameter 76 mm, maximum operating pressure 4 bar; manufacturer: Sati Trading; sourced from Bologna, Italy.
Pressure Transmitter	4–20 mA, 0–10 bar, reference accuracy ±0.3%; manufacturer: Endress and Hauser; model: Cerabar PMC21-1R60/0; sourced from Milan, Italy.
Electric Multimeter	conformity accuracy of cl.0.5 for voltage, cl.0.5 for current, cl.0.5 for active power (accordingly to [20]); manufacturer: IME; model: Nemo 72 Le; sourced from Milan, Italy.

The pilot plant installation has been completed on 2nd August 2018, and the pilot plant is still running.

2.4. Pilot Plant Configurations Tested

The pilot plant has been tested with different configurations, which differ in the following parameters: (i) inverter frequency (i.e., water flowrate that feeds each ejector), (ii) size of the diameter d of the central nozzle of the ejector, and (iii) number of radial nozzles of the ejector. In particular, the frequency of the inverter and the related water flowrate has been preliminary assessed to identify under which working conditions each ejector can reach the maximum allowed suction efficiency Ψ, which has been set to 20%, based on previous experience. Table 3 summarizes the different configurations tested in the 12 months of monitored operation of the pilot plant. The value of the central nozzle diameter d is not included in the text since it is an information covered by industrial secrecy; the ejector n°1 nozzle is considered as reference size d_0.

Table 3. Characteristics of pilot plant configurations tested in Cattolica. The frequency of each inverter is expressed as a percentage in the range 12.5–50 Hz, being 0% corresponding to 12.5 Hz.

Ejector #	Configuration #	Central Nozzle	N° of radial Nozzles	Inverter Frequency
1	1	$d = d_0$	18	78%
	2	$d = d_0$	18	70%
	3	$d = d_0$	6	Variable
2	1	$d = 0.92 \times d_0$	6	92%
	2	$d = 0.92 \times d_0$	6	69%
	3	$d = d_0$	6	Variable

In the first configuration the pilot plant operated in conditions close to the maximum suction capacity of the ejectors. In the second configuration the pilot plant operated at a reduced frequency of both inverters. It should be noted that the ejectors installed for configurations 1 and 2 were not modified. In the third configuration, both the ejectors were substituted; the same ejectors were mounted on each line (central nozzle $d = d_0$ and 6 radial nozzles). Secondly, the inverter control has been varied in relation to the use of the towing basin and of the meteorological conditions (i.e., higher inverter frequency during ships launch and/or Tavollo stream flood).

2.5. Monitoring Plan

The pilot plant has been monitored in the period from August 2018 to July 2019. The efficacy of the plant has been assessed through bathymetries, while the efficiency of the plant has been evaluated in terms of power consumption. Operation and maintenance activities have been monitored to estimate operation and maintenance costs over the pilot plant expected lifetime.

2.5.1. Bathymetries

The bed of water basin morphology is shaped by sediment transport, which in turn is a function of the local interaction between stream flow and streambed sediment. A variety of survey methods have recently been developed to map water basin bathymetry [21]. Nevertheless, the highest the required accuracy, the highest the cost for the morphology assessment of the bed of water basin. In CO-EVOLVE project the scope of bathymetry monitoring had two main objectives: verify the effectiveness of the pilot plant (i.e., keeping the water level at a certain value over the time) and assess the impact of discharge pipelines. For the scope of the study, it was assumed that the realization of manual bathymetries and/or the use of the echo sounder Eco 151dv (manufacturer: Garmin; sourced from Milan, Italy) can be considered acceptable in terms of measurement accuracy.

Two bathymetries maps have been designed by the University of Bologna for the Marina of Cattolica personnel, which was in charge for the streambed monitoring activities. The bathymetries maps are included in the Supplementary Materials. The first map is a general one, for the evaluation of the impact of discharge pipelines of the pilot plant on the streambed morphology at a wider scale, while the second map is focused only on the towing basin. Three different areas have been identified in the general map: an area A which is coincident with the discharge area of the pilot plant; an area B, which is 30 m downstream from the area A; and area C, which is more than 100 m downstream from the area A (and so undisturbed from the pilot plant operation). Figure 7 shows the position of the measuring points in the general map. Figure 8 shows the position of the measuring points in the towing basin area.

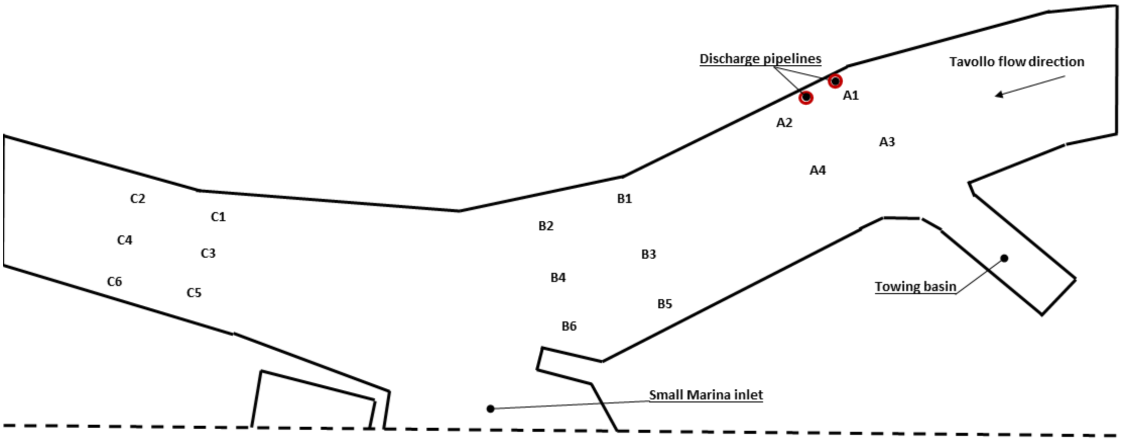

Figure 7. Position of the selected bathymetries measuring points for the evaluation of ejectors discharge impact.

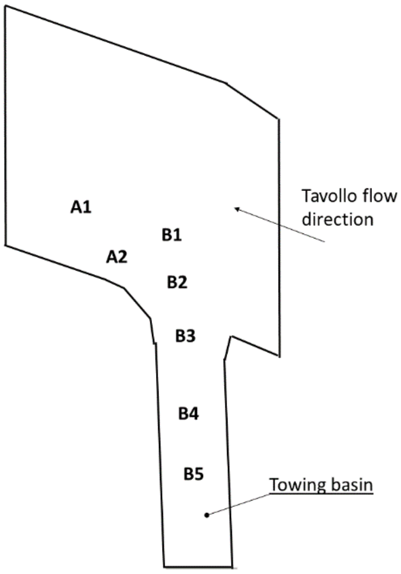

Figure 8. Position of the selected bathymetries measuring points for the evaluation of ejectors effectiveness in the towing basin area.

The bathymetries were periodically realized by the personnel of the new small marina. The bathymetric results were shared with Emilia-Romagna region, Cattolica municipality, marinas and shipyard managers, local office of the port authority, University of Bologna and Trevi SpA.

2.5.2. Energy Consumption

The power consumption of the whole pilot plant is measured by an electric multimeter. This device is used to account the total energy consumption of the pilot plant, which is registered and saved in the database. The measure includes pumps power consumption plus electric panel auxiliaries. On the other hand, the power consumption for each pump is given by the inverters and is registered in the database, too.

2.5.3. Maintenance Activities

Each maintenance activity has been recorded, including notes about specific activities carried out, people involved, means employed, and needed consumables and/or equipment. The personnel involved in the maintenance activities came from the marinas, the shipyard, the University of Bologna and Trevi SpA.

2.6. Economic Assessment

Table 4 summarizes the parameters that have been used for the economic assessment of the pilot plant. Electric energy cost is about 0.22 €/kWh, including taxes. Personnel cost per hour of about 25 €/h has been considered in the maintenance cost computation, while the use of means has not been considered as a cost. The expected life of the pilot plant is estimated in 10 years; the pumps are the most critical devices, which may require a substitution before the 10 years limit. The substitution cost of both pumps (divided per the 10 years) have been included in Table 4 as extraordinary maintenance costs. The yearly costs generated by pilot plant operation per 10 years have been discounted by considering an interest rate of 1.5%. The mean yearly cost for plant operation and maintenance has been computed and discounted for the pilot plant expected life. Dredging costs may vary in a wide range, from 2.7 to 33.2 Euro per cubic meter dredged [9].

Table 4. Economic parameters.

Parameter	Value
Pilot Plant Capital Cost (€)—VAT Excluded	49,000
Energy Cost (€/kWh el)	0.22
Personnel Cost (€/h)	25
Pilot Plant Expected Life (years)	10
Extraordinary Maintenance Costs (€/year)	750
Interest Rate (%)	1.5

3. Results and Discussion

3.1. Pilot Plant Efficiency

The pilot plant operation can be divided in three periods, which differ accordingly to the three configurations defined in Table 3. In the first period (2 August 2018 to 18 December 2018) the pilot plant operated in conditions close to the maximum allowed suction efficiency of the ejectors. The measured power consumption in the first period is 23,320 kWh, with total working hours of 3168 h (mean power consumption of 7.34 kW for the whole pilot plant).

In the second period considered (18 December 2018 to 19 June 2019) the pilot plant operated at a reduced frequency of both inverters. The pilot plant consumed 23,418 kWh for total working hours of 4226 h. The result was a mean power consumption of 5.54 kW. It should be noted that the reduction in consumption was achieved simply by modulating the ejectors' feed pumps to a lower frequency, having the ejectors installed for both periods indicated above the same characteristics. Therefore, in the second period of experimental campaign the pilot plant operated by consuming 25% less than in the first period.

In the third (and last) period (19 June 2019 to 22 August 2019) a further tentative to reduce the pilot plant's mean power consumption has been carried out. Two different strategies have been put in place: Firstly, the ejector n°2 has been substituted by an ejector with a central nozzle diameter 10% larger. Secondly, the number of nozzles of ejector n°1 has been reduced. Therefore, in the third phase of the experimental campaign, the ejectors installed in the two lines were the same. Furthermore, the inverter control has been varied in relation to the use of the towing basin and of the meteorological conditions (i.e., higher inverter frequency during ships launch and/or Tavollo stream flood). Table 5 summarizes the various operating modes tested in the last period of experimental tests. Table 5 shows that only in three times (19 June–22 June; 19 July–27 July; 30 July–22 August) it has been possible to reach a mean power consumption reduction if compared with the second period of experimental tests. The reduction is in the range 1–8%.

Table 5. Operating modes tested in the third period (19 June 2019 to 22 August 2019) of experimental tests. The frequency of each inverter is expressed as a percentage in the range 12.5–50 Hz, being 0% corresponding to 12.5 Hz.

Period	Frequency Inverter #1	Frequency Inverter #2	Power Consumption	Working Hours	Mean Power Consumption
19 June–22 June	70%	70%	362 kWh	71 h	5.10 kW
22 June–25 June	85%	65%	410 kWh	65 h	6.31 kW
25 June–26 June	90%	85%	120 kWh	16 h	7.51 kW
26 June–11 July	85%	65%	2370 kWh	368 h	6.44 kW
11 July–16 July	95%	80%	945 kWh	117 h	8.08 kW
16 July–19 July	85%	65%	470 kWh	76 h	6.18 kW
19 July–27 July	70%	65%	1049 kWh	198 h	5.30 kW
27 July–30 July	90%	80%	630 kWh	77 h	8.18 kW
30 July–22 August	75%	65%	2970 kWh	539 h	5.51 kW
Total	-	-	9326 kWh	1527 h	6.11 kW

Nevertheless, in the last experimental period, both due to significant meteorological events and in relation to the shipyard's operation, there were also time intervals in which mean power consumption was higher than in the second experimental period. The result is a mean power consumption in the whole third period that is 6.11 kW. Therefore, particular attention must be paid to the variable manual management of the operating conditions, as the transition from one regime to the other does not take place automatically but at the discretion of the operator.

On the basis of the above mentioned results, it was decided not to test a fourth period of operation, in which the control idea would be of maximizing the yield of the pilot plant in conjunction with the operation of the shipyard (i.e., during daylight hours and working days), leaving the system at night to a minimum value, or switched off. This fourth operating condition has not been tested since (i) putting the system to a minimum power consumption may be risky in the absence of a designated operator who updates the operating regime in the event of adverse weather forecasts or conditions, and (ii) switching off the system is an option that was discarded by following a direct involuntary test. In fact, in February there was a power blackout: the analysis of the pilot plant after seven days of forced switched off of the pilot plant showed a high fouling of the ejectors. Moreover, the pilot plant shutdown strategy should be properly designed, since a continuous start–stop cycle of the pumps could have negative consequences on the long-term reliability of the pumps themselves.

3.2. Pilot Plant Effectiveness

3.2.1. Monitoring of Discharge Area

The comparison of the measuring points identified in Figure 7 are reported in the Supplementary materials. The bathymetric measurements started on May 2018 (i.e., three months before pilot plant installation) and continued up to May 2019 (i.e., nine months after pilot plant started). Bathymetries show that areas A and B have similar results in terms of mean bathymetric variation before and after pilot plant operation started. Area C shows a different mean variation, which is, however, coherent before and after pilot plant operation started, since it reveals a lower impact of sedimentation than in areas A and B. Therefore, the monitoring of streambed showed that the impact of pilot plant operation in the discharge area is a near-zero impact since no measurable water depth variation can be identified in comparison with the period before pilot plant operation.

3.2.2. Monitoring of Ejectors Area

The comparison of the measuring points identified in Figure 8 are reported in Table 6. The bathymetric measurements started on August 2018 (pilot plant start) and continued up to July 2019 (i.e., 12 months after pilot plant started).

Table 6. Bathymetries measured in the timeframe from August 2018 to July 2019. The variation between two consecutive periods is reported, as well as the variation in relevant longer period. The underlined values are the ones measured wherein the ejectors were installed. The position A1−A2 and B1−B5 are the ones defined in Figure 8.

	Date	Bathymetries (m)						
		A1	**A2**	**B1**	**B2**	**B3**	**B4**	**B5**
1	02 August 2018	2.00	3.00	2.40	2.40	2.30	2.70	2.70
2	23 August 2018	2.00	3.35	2.35	2.35	2.25	2.55	3.05
	Variation (2-1)	0.00	0.35	−0.05	−0.05	−0.05	−0.15	0.35
3	10 September 2018	2.15	3.45	2.75	2.35	2.65	2.85	3.05
	Variation (3-2)	0.15	0.10	0.40	0.00	0.40	0.30	0.00
4	12 October 2018	2.20	3.5	3.40	2.50	2.40	2.60	3.30
	Variation (4-3)	0.05	0.05	0.65	0.15	−0.25	−0.25	0.25
5	12 November 2018	2.20	3.30	2.80	2.50	2.70	2.80	3.00
	Variation (5-4)	0.00	−0.20	−0.60	0.00	0.30	0.20	−0.30
6	18 December 2018	2.45	3.55	2.65	2.65	2.65	2.65	2.95
	Variation (6-5)	0.25	0.25	−0.15	0.15	−0.05	−0.15	−0.05
	Variation (6-1)	0.45	0.55	0.25	0.25	0.35	−0.05	0.25
7	23 December 2018	2.50	3.40	2.60	2.60	2.50	3.00	2.70
	Variation (7-6)	0.05	−0.15	−0.05	−0.05	−0.15	0.35	−0.25
8	03 January 2019	2.60	3.50	2.50	3.30	2.60	3.20	3.00
	Variation (8-7)	0.10	0.10	−0.10	0.70	0.10	0.20	0.30
9	08 January 2019	2.60	3.40	2.50	2.40	2.70	2.70	3.40
	Variation (9-8)	0.00	−0.10	0.00	−0.90	0.10	−0.50	0.40
10	05 February 2019	2.45	2.85	2.55	2.45	2.85	2.45	2.95
	Variation (10-9)	−0.15	−0.55	0.05	0.05	0.15	−0.25	−0.45
11	20 February 2019	2.35	3.65	2.75	2.75	2.45	2.35	3.25
	Variation (11-10)	−0.10	0.80	0.20	0.30	−0.40	−0.10	0.30
12	13 March 2019	2.35	3.35	2.65	3.45	2.55	3.05	3.15
	Variation (12-11)	0.00	−0.30	−0.10	0.70	0.10	0.70	−0.10
13	17 May 2019	2.30	3.55	2.30	2.90	2.30	2.40	3.10
	Variation (13-12)	−0.05	0.20	−0.35	−0.55	−0.25	−0.65	−0.05
	Variation (13-6)	−0.15	0.00	−0.35	0.25	−0.35	−0.25	0.15
	Variation (13-1)	0.30	0.55	−0.10	0.50	0.00	−0.30	0.40
14	13 June 2019	2.00	2.40	2.20	2.30	2.20	3.40	2.80
	Variation (14-13)	−0.30	−1.15	−0.10	−0.60	−0.10	1.00	−0.30
15	17 July 2019	2.25	2.25	2.35	2.45	2.45	2.45	2.65
	Variation (15-14)	0.25	−0.15	0.15	0.15	0.25	−0.95	−0.15

The pilot plant effectiveness has been evaluated by considering the three different operation periods as defined in Table 3. In the first period (2 August 2018–18 December 2018) the pilot plant was able to increase the streambed depth in the monitored points up to 0.55 m. In the same period, the monitored points of the discharge area showed a mean depth increase of 0.20 m (see Supplementary materials). Therefore, it is demonstrated that the ejectors positively contributed to the control of streambed depth.

In the second period (18 December 2018–19 June 2019) the pilot plant impact should be evaluated with more attention. In fact, up to May 2019 the pilot plant still demonstrated to work well, since in the area influenced by the ejectors (mainly points A2, B2, and B5) a depth increase or, at least, no depth variation can be observed with the 18 December 2018 bathymetries, while in the same period the mean streambed depth variation at the ejectors discharge area is −0.2 m (see Supplementary materials). So, also in the second operation period the pilot plant guaranteed to keep the streambed at a constant level.

Nevertheless, the last two measuring sessions in Table 6 showed a change in the pilot plant effectiveness trend. In the case of 13 of June 2019 bathymetry, since no elements arise from the analysis of the recorded data from the programmable logic controller (PLC), and by considering the relevant performance of the ejector installed near point B4, it is possible that the measurement in point A2 has not been properly performed, i.e., the hole protected by the ejector has not been identified. By analyzing the bathymetry of 17 July 2019, it is clear that something happened in the ejectors suction capacity, since most of the measuring points lost depth (in particular, points A2 and B4). The main cause of the negative performances observed in the last period can be attributed to the lack of maintenance occurred after some non-continuous full of the Tavollo stream that occurred between the last ten days of June 2019. The combination of a reduced suction capacity due to the fouling of the external pumps filters and of the highest rate of sediment transported by the stream had negatively impacted on the effectiveness of the entire system. The conclusion is that ordinary maintenance is crucial to guarantee the effectiveness of the system, and such information has been used in the paper to properly assess the ordinary maintenance costs of the pilot plant on a wider industrial perspective.

Table 6 also shows that the ejectors have been moved in different positions during the monitoring period. This operating mode has been adopted to increase the effectiveness of the pilot plant. The change of position was simplified by the specific of the site, which made possible to connect the ejectors to the docks by leaded ropes. In fact, due to the characteristics of the deposited sediment, the impact of the ejectors in terms of water depth increasing was limited to a very small area around the ejectors themselves. So, through manual small movements of the ejectors it was possible to cover a larger area than a fixed installation. In particular, ejector n°1 has been mainly places in A2 but has been also moved to positions B1 and B2, while ejector n°2 was mainly moved between positions B3, B4, and B5. Ejector n°1 was moved only during monitoring action or maintenance activities (i.e., when the ship was present), while ejector n°2 could be easily moved without any support equipment from the docks. The time spent by the personnel in these kinds of operations can be neglected and had no economic impact on the pilot plant operation.

3.3. Economic Assessment

3.3.1. Ordinary Maintenance Costs Evaluation

The maintenance costs have been estimated on the basis of the activities carried out in the first year of operation of the pilot plant. Table 7 shows the complete list of maintenance activities in the period August 2018–August 2019. Information about number of people involved, equipment, and consumables is included.

The total number of registered maintenance operations is 12, with a mean duration of 1.3 h and a mean number of people involved of about four. Boat, pressure washer, and forklift are the equipment used in some of the operations: the costs related to the use of the equipment are not considered in this study, since they were available in the shipyard. Moreover, consumables were needed to complete some maintenance actions: a yearly cost for consumable of about 500 € can be estimated.

The most important maintenance activities were related to pumps cleaning. Two different cleaning actions were carried out: external cleaning (i.e., cleaning of the external filter, see Figure 9) and internal cleaning (i.e., cleaning of the cooling sleeve and of the internal filter), the second one being more complicated and time consuming, but mainly related to organisms proliferation (i.e., mussels) in specific period of the year. A tentative has been made to correlate the progress of pumps fouling with the pressure monitoring at the pumps outlet (PT1 and PT2 in Figure 4). The working pressure is one of the parameters to be monitored when the optimization of maintenance scheduling is required [22].

Table 7. List of maintenance activities carried out in the period August 2018–August 2019.

Activity	Date	Time (h)	# People	Equipment	Consumables
Pump n°2 and ejector n°1 cleaning	26 September 2018	1.50	3	Boat Pressure washer	Plastic straps Teflon
Pump n°1 cleaning	28 September 2018	1.50	3	Boat Pressure washer	Plastic straps Teflon
Antifouling (on pumps)	03 October 2018	1.00	6	Boat Pressure washer	Antifouling
Antifouling (on pumps)	04 October 2018	3.00	6	Boat Pressure washer	Plastic straps Teflon Antifouling
Pressure transmitter PT1 dismounted	10 January 2019	0.50	2	Boat	Teflon
Pressure transmitter PT1 installed	11 February 2019	0.50	2	Boat	Teflon
Pumps cleaning	12 March 2019	1.00	5	Pressure washer Forklift	-
Pumps cleaning and pressure transmitter PT1 dismounted	02 May 2019	2.00	7	Boat Pressure washer Forklift	-
Pumps cleaning and pressure transmitter PT1 installed	06 June 2019	2.00	5	Boat Pressure washer Forklift	-
Ejectors substitution (for cleaning)	19 June 2019	1.00	3	Boat	Teflon
Discharge line substitution on ejector n°2	27 June 2019	1.00	4	Boat Forklift	30 m discharge pipeline
Metal clamp substitution on pump n°2 feeding pipeline	01 July 2019	0.25	3	Boat	Metal clamp

Figure 10 shows the pressure variation at the pump n°2 outlet in the period between two external cleanings (2 May 2019 and 6 June 2019). In the same figure also power consumption and motor speed of the pump are included. Figure 10 shows how two different pressure drops can be highlighted in the period (approximatively on 13 May and on 28 May). Nevertheless, between the two pressure drops there is a pressure recovery from 2.8 bar to 3.1 bar. The pressure increasing can be read as a reduction of fouling in the external filter, or an increasing of ejector n°2 fouling, or a combination of both. The pilot plant control system generates several alarms, including high and low pressure alarms. So, an effective setting of low pressure alarm (i.e., 5–10% less of the pressure in "clean" conditions) can help plant operators to optimize pumps maintenance schedule. A pressure reduction can be read also as a decreasing of plant hydraulic resistance, which may be caused, for example, by a water loss at pumps outlet. However, this is not the case; in fact, both the pressure drops in Figure 10 are followed by a power consumption decrease, being the motor speed kept constant over the period. In case of water loss, the power consumption should be kept constant, or at least increase, depending on the water loss relevance.

Figure 9. Fouling of the external filter of the pump; picture taken on 2 of May 2019, before cleaning.

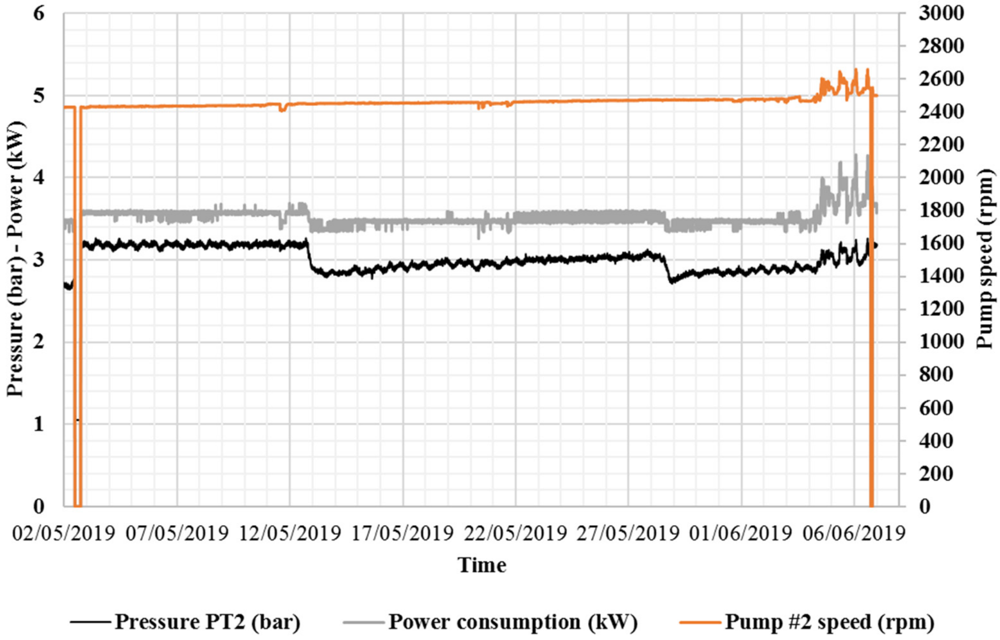

Figure 10. Monitored pressure, power consumption and motor speed on ejector line n°2 in the period from 2nd of May 2019 to 6th of May 2019 (between two external cleaning operations).

3.3.2. Mean Yearly Cost for Operation and Maintenance of the Pilot Plant

Power consumption is the main yearly operation cost of the pilot plant. The energy consumption of the pilot plant may depend on the control strategies, as demonstrated in Section 3.1, a mean electricity consumption of 5.5 kW can be assumed for a pilot plant effective operation. The plant is supposed to work for a total amount of 8475 h per year: this number has been computed by considering the hours requested for plant maintenance activities that require the plant shut down.

The mean yearly cost for the operation and maintenance of the pilot plant has been computed on the basis of the information included in Tables 4 and 7. The lifetime of the plant is considered to be 10 years; the yearly costs have been discounted over that period. The ordinary maintenance costs (manpower and consumables) have been doubled in comparison with the ones identified in Table 7 to take into consideration the need of guarantee the optimal operation of the plant, in particular regarding pumps cleaning. Table 8 summarizes the results of the economic analysis. The whole discounted costs for plant installation, operation and maintenance for ten years is equal to about 188,000 €, i.e., a mean yearly cost of about 19,000 €.

Table 8. Discounted yearly operation and maintenance costs of the pilot plant.

Yearly Cost	0	1	2	3	4	5	6	7	8	9	10
Capital cost (k€)	49	-	-	-	-	-	-	-	-	-	-
Energy bill (k€)	-	10.1	10.0	9.8	9.7	9.5	9.4	9.2	9.1	9.0	8.8
Manpower (k€)	-	3.1	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.7	2.7
Consumables (k€)	-	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Extraordinary maintenance (k€)	-	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6
Total (k€)	49	14.9	14.7	14.5	14.2	14.0	13.9	13.6	13.5	13.3	13.0

3.3.3. Comparison with Maintenance Dredging Operations

The economic comparison between the pilot plant and maintenance dredging is not immediate for the following reasons. First of all, the technologies work with different approaches, while dredging removes in a limited time a certain amount of sediment from a specific area, the pilot plant continuously sucks and boosts away the sediment that is coming to an undefined area. Secondly, the volume of dredged material can be measured through the differences observed in bathymetries realized before and after dredging and/or by considering dredge storage volume. This approach is not effective to measure the volume of material handled by the pilot plant, since the pilot plant works also with suspended material, and not only with the deposited one.

If the area of the towing basins is considered, a relatively high cost for dredging operations can be predicted, since the area is not easy to access for small-medium size dredging equipment. So, it is possible to foresee a cost of about 20–25 € per cubic meter dredged, which corresponds to the higher values of the interval indicated in literature.

The pilot plant yearly cost has been computed in 19,000 €. So, to even out the cost of dredging the pilot plant should handle about 630 m^3 of sediment in one year. From previous experiences [14,16], it can be demonstrated that in Cattolica pilot plant configuration one ejector can move up to about 1.5 m^3/h of sediment in operating conditions close to maximum allowed suction efficiency. That is, for the pilot plant, a theoretical maximum capacity of sediment handling of about 25,600 m^3. Therefore, it can be assumed that the pilot plant can guarantee a lower specific cost for sediment handling if compared with dredging, since this result can be achieved if the pilot plant works at more than 2.5% of its maximum capacity, which is indeed highly probable.

On the other hand, it should be stressed that investment and operation costs are not the only economic parameters to be taken into consideration in the comparison between the pilot plant and dredging. There are several indirect economic costs (or benefits) that can be due to the fact that the towing basin is less or more navigable. In fact, dredging can only temporarily solve the problem of sedimentation since deposits can build up between one dredging operation and the next and limit or block dock activities. Conversely, the pilot plant can work continuously; thus, preventing sedimentation and guaranteeing towing basin operation throughout the year. Nevertheless, indirect costs for dredging and benefits for the pilot plant due to sedimentation are difficult to estimate.

As a result, it should be taken into consideration that the cost for sediment handling can be an important parameter in the economic comparison between the pilot plant and dredging, but it is not conclusive. Further investigations are needed to monitor economic benefits over a longer time frame (2–5 years) to verify which kind of revenues can be directly and indirectly produced by the pilot plant operation.

4. Conclusions

An innovative technology for sediment management in ports and channels was tested and monitored in Cattolica (Italy) from August 2018 to July 2019. The pilot plant is characterized by the presence of two jet pumps that have been installed in a towing basin with the main scope of keeping the proper water depth for the whole period; thus, ensuring the operation of the economic activities that are dependent by the towing basin operation. The monitoring activities demonstrated that the technology can be both effective and efficient. Nevertheless, the monitoring assessment also underlined how the ordinary maintenance, and in particular the pumps cleaning, is crucial to guarantee the effectiveness of the plant over the time. Further monitoring actions are needed to measure the economic benefits produced by the continuous operation of the towing basin.

Starting from the 1 January of 2020 the plant operation is completely in charge of the Cattolica municipality. Due to the positive results produced by the pilot plant, it is under evaluation the opportunity to implement the existing system to guarantee a navigable channel from the towing basin to the small marina.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-1312/8/9/686/s1, Figure S1: General bathymetry map, Figure S2: Bathymetry map for the towing basin, Table S1: Bathymetries measured in the timeframe from May 2018 to May 2019.

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