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Conservation actions for restoring the coastal lagoon habitats: Strategy and multidisciplinary approach of LIFE Lagoon Refresh

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The Habitat Directive of European Union lists Costal Lagoons (habitat code 1150*) among priority habitats because they are in danger of disappearance. Natural ecosystems may recover from anthropogenic perturbations; however, the recovery can follow natural restoration or it can be redirected through ecological restoration by anthropogenic intervention. Accordingly, by collecting the available theoretical indications for restoration of estuarine and coastal areas, a methodological approach was detailed andit can be summarised into five issues: (i) Environmental context from which it began; (ii) Desired state to be achieved; (iii) Policies and socio-economic context; (iv) Typology of recovery and/or improvement of habitats and ecosystems; and (v) Methods for monitoring the impact of the project. The project strategy, management and measures of LIFE Lagoon Refresh were also presented and discussed, as a case study for the implementation of the multidisciplinary approach for restoration ecology in transitional waters. The project takes place in the northern Venice Lagoon (Italy), started in 2017 and it lasts 5 years. In the Venice Lagoon, since the 20th century, strong reductions of the typical salinity gradient of buffer areas between lagoon and mainland, and of reedbed extensions have occurred due to historic human interventions, with negative consequences on coastal lagoon habitats. To improve the conservation status of habitats and biodiversity of the area, the LIFE Lagoon Refresh project included several conservative actions, which are (i) the diversion of a freshwater flow from the Sile River into the lagoon; (ii) the restoration of intertidal morphology, through biodegradable structures; (iii) the reed and aquatic angiosperm transplantations with the involvement of local fishermen and hunters, and (iv) the reduction of hunting and fishing pressures in the intervention area. To achieve the restoration of the lagoon environment, the strategy of the project covered a combination of different aspects and tools, such as planning activities, through the involvement of local Institutions and communities; stakeholder's involvement to increase awareness of environment conservation and socioeconomic value improvement; an ecological engineering approach; numerical models as supporting tool for planning and managing of conservation actions; environmental monitoring performed before and after the conservation actions.

KEYWORDS

Venice Lagoon, ecological restoration, salinity, reedbeds, habitats directive, birds directive, water framework directive

Introduction

In last decades, many lagoon and coastal marine ecosystems, of exceptional ecological, recreational, and commercial value, have experienced a loss of their environmental status (De Wit et al., 2020).

The European Union (EU) Habitat Directive lists, in Annex I, sites of community interest that require the designation of special areas of conservation. Among these sites, some are considered of priority interest because they are in danger of disappearance, such as the priority habitat of Coastal lagoons (Habitat code: 1150*), defined as expanses of shallow coastal saltwater, of varying salinity and water volume, wholly or partially separated from the sea by sand banks, or, less frequently, by rocks. The Habitat Directive also details information about salinity, which may vary from brackish water to hypersalinity depending on several conditions, such as rainfall, evaporation, tidal exchange, etc. (European Commission, 2013). Moreover, the EU Water Framework Directive (WFD, 2000/60/EC), aims at improving the ecological status of water bodies, such as transitional waters, advocating the pro-active approach of the restoration ecology (De Wit et al., 2020). Multiple stressors, including hydromorphological modifications, pollutants, excess of nutrient inputs, sediment budget unbalance and other ecosystem alterations, which can affect resources through single, cumulative or synergistic processes, can cause their degradation (De Wit et al., 2020). From a morphological and hydrodynamic point of view, each lagoon has peculiar characteristics closely related to the amount of freshwater inputs, tidal fluctuations and human interventions that, very often, have modified these areas either by land reclamation, or by exploitation of fish resources, or for navigation (Facca et al., 2020). The threats and pressures determining the unfavourable/bad status of European coastal lagoons are numerous. Among these, the main are: changes in water bodies conditions, pollution of surface water, fishing and harvesting of aquatic resources, direct destruction or reduction of habitats due to the construction of infrastructure (e.g., ports), dredging of shipping channels, and the creation of facilities for the regulation of hydrodynamism (Newton et al., 2014; European Environment Agency, 2021).

Natural ecosystems may recover from perturbations being able to return to the state before the disturbance (resilience). However, depending upon time scales of duration, extension and intensity of perturbations, the return to the historic trajectory of the ecosystem may: (i) follow natural restoration though secondary succession; (ii) be redirected through ecological restoration by anthropogenic intervention; or (iii) be unattainable (Borja et al., 2010).

Many theoretical indications exist concerning restoring of estuarine and coastal area; the transfer of theoretical approach for the design and actual implementation of restoration project is still an issue of high scientific interest.

The Venice Lagoon is one of the largest and most important coastal transitional ecosystems of the Mediterranean Sea (Tagliapietra et al., 2009). Human presence has constantly modified the original morphology and hydrology since the city's foundation and the Venetians tried to modify the environment in the attempt to preserve economic interests, human health and for defence purposes (Guerzoni and Tagliapietra, 2006; Solidoro et al., 2010). Among anthropogenic actions, the management of freshwater and sediment loads from the drainage-basin tributaries was particularly relevant to prevent sedimentation in marginal areas and to avoid health problems associated with malaria. The main intervention realised from the second half of the 16th century was the diversion of main rivers that flowed into the lagoon (Piave and Sile rivers in the northern lagoon, Brenta and Bacchiglione rivers in the southern lagoon). Those hydrological modifications caused profound changes in morphology and ecology of the lagoon. One of the main effects was a deficit in the sediment budget of the lagoon, that led to prevalence of erosion processes, with a strong reduction of salt marshes and deepening of tidal flats. The reduction of hundreds cubic metres per second of freshwaters that flowed into the lagoon resulted in an increase of salinity in the inner parts and a loss of the typical salinity gradient of that environment (D'Alpaos, 2010; D'Alpaos and Carniello, 2010). The increase of salinity modified heavily habitats and ecology of those areas, leading to expansion of mudflats instead of typical lagoon oligohaline habitats. Alterations of geomorphological and physical properties clearly affected spatial distribution, structure, and composition of vegetation and fauna communities. The reedbed of *Phragmites australis* disappeared almost everywhere. Historical maps demonstrate a constant decline of salt marshes from 255 km^2 in early 1,600, to 170 km^2 in 1,900 and 47 km^2 in 2000, respectively, mainly in the inner areas, where reeds were dominant (D'Alpaos, 2010). These changes affected heavily biological communities, leading to a replacement of lagoon species with predominantly marine species, and a shift toward assemblages with more tolerance to eutrophic conditions (Solidoro et al., 2010).

In this context, LIFE Lagoon Refresh is the first project aimed at restoring salinity gradient in the Venice Lagoon, and the scope of this manuscript is illustrating the project strategy, management and measures adopted as a case study for the application of the multidisciplinary approach of restoration ecology in transitional waters. The major strengths of the study are the environmental-friendly methodology employed that did not compromise the other uses of the lagoon area, the attainability of the results obtained and the evident potential of long-term strategies of conservation and management; these are especially significant for the Venice Lagoon, which is unique in its configuration, location, ecosystem services, as well as in its historical, artistic, urban, and economic relevance.

Methodological approach

With reference to the approaches proposed by USEPA (2000), Elliott et al. (2007), and De Wit et al. (2020), the planning and execution stages of an ecological restoration project should consider five essential issues: (i) Environmental context from which it began; (ii) Desired state to be achieved; (iii) Policies and socio-economic context; (iv) Typology of recovery and/or improvement of habitats and ecosystems, and (v) Methods for monitoring the impact of the project (**Table 1**).

The collection of information should include not only chemical, physical, hydrological, geomorphological, biological, and ecological data, but also information on the existing impact and pressures, the current socio-economic uses of the area, ongoing and foreseen management plans and programmes, and any constraints and limitations. All these information contribute to the restoration process and define the baseline inventory.

Environmental context

The existing environmental information and data collected with monitoring activities before the project realisation define the site baseline condition at the beginning of the restoration process. The information on biotic and abiotic elements of the site, as well as pressures, threats and impacts, are as a key initial step to understand what the desirable and possible state is considered in terms of restoration target (Gann et al., 2019). At the same time, it is essential to take into account the socio-economic uses (fishing, hunting, farming, and tourism, etc.), the plans and programmes of the area and any constraints and limitations, to prevent further difficulties and barriers for the project implementation.

Desired state to be achieved

In an ecological restoration project, it is fundamental to have clear in mind the desired state to be achieved. As reported by Elliott et al. (2007), ecological restoration should be based on the identification of a reference state, also turning to reference site, namely areas that are comparable in structure and function to the proposed restoration site before it was degraded. When the original condition of the natural habitat is unknown, a combination of qualitative knowledge of the original habitat type with information deriving from still existing habitats can be done to provide a quantitative assessment of the state to be achieved and the expected results (Lewis, 1990). Indeed, it is possible to use both historical information on altered or destroyed sites, and/or those of similar and relatively healthy ones, as a guide for the project (Clewell and Aronson, 2013).

Restoration projects need clear goals and objectives in order to be successful. Direct implementation of goals and objectives provides standards for measuring the success; they must be linked to expected results, which should be measurable with specific indicators (Gann et al., 2019). The expected results for habitat and species restoration are given in a quantitative way, but the quantification can be decided by expert judgement referring to reference sites.

Policies and socio-economic context

Ecological restoration is a solutions-based approach that engages communities, scientists, policymakers, and land managers, thus the analysis of the policies and socio-economic context need to be considered during the development of the restoration project. In their proposal of conceptualisation, placing the ecological restorations in societal context, De Wit et al. (2020) posed two interesting questions. The first is related to the value that human populations, and particularly stakeholders, give to ecological restoration practice; with

TABLE 1 Elaboration of the theoretical elements from literature (see reference in the text).

(1)	**Environmental context from which it began**
	Chemical, physical, hydrological, geomorphological, biological, and ecological data
	Impacts and pressures
	Socio-economic uses of the area
	Plans and programmes of the area
	Constraints and limitations
(2)	**Desired state to be achieved**
	Which status to refer to? Reference state, historical reference, new status
	Which are the expected results? Qualitative and/or quantitative
	Which are the tools available to predict quantitative results? Hydrodynamic models, habitat suitability models, etc.
(3)	**Policies and socio-economic context**
	How is the ecological restoration practice evaluated by human populations and particularly by stakeholders?
	Involvement of stakeholder, quantification of ecosystem services
	Is the ecological restoration practice congruent with other type of legislation (local, national, and European, etc.)?
	Single low or multiple legislation aspects
	Is there a broader management context? Different measures in the area and/or same measures in different site of the area
	Is it possible to ensure the long-term viability of the restored area? Minimising the need for maintenance, favouring the self-sustainability
(4)	**Typology of recovery and/or improvement of habitats and ecosystems**
	Natural recovery once the stressor is removed
	Anthropogenic interventions
	○ in response to a degraded or anthropogenically changed environment
	○ in responses to a single stressor
	○ Habitat enhancement or creation
	The necessary eco-engineering measures (in the cases of anthropogenic interventions)
	○ Is it necessary to restore physical and/or chemical and/or morphological environments?
	✓ Change in flow regimes and siltation
	✓ Bottom elevation alterations
	○ Is it necessary to restore biological and ecological integrity?
	✓ Transplanting seagrass
	✓ Transplanting reed beds
(5)	**Methods for monitoring the impact of the project**
	Choice or implementation of tools for monitoring physical, chemical, morphological, and biological parameters in a quantitative way (indicators, models, etc.)
	Monitoring before the project to evaluate the status zero (baseline)
	Monitoring during the project for finding out whether goals of Methodological approach are being achieved
	Applied "mid-course" adjustments. Adaptive management
	Monitoring post-project and evaluate whether additional actions or adjustments are needed

particular regard to their perceptions and wishes for desired states of the ecosystem. The latter is the conflicts that can arise because of different objectives and concepts, as the ecological restoration practice should be congruent with other types of legislation.

The key to ensure that both nature and society mutually benefit is to recognise the expectations and interests of stakeholders, involving them directly. All categories of stakeholders, potentially influenced by the project, such as institutions, local and national management bodies, local community, associations, fishermen, and hunters, should be analysed in the earliest stages, thus addressing to both stakeholders who could benefit or have a negative impact from restoration actions due to conflicting uses. Indeed, as reported by Gann et al. (2019), stakeholders can make or break a project.

Again, to achieve better results with ecological restoration in the policies context, the projects have to integrate strategically within larger restoration programmes. As principles of wetland restoration described by USEPA (2000), it is essential a design based on the entire watershed, not just the part of the waterbody that may be the most degraded site. Restoration plans should identify dispositions for site maintenance after project completion, and ensure the long-term viability of a restored area by minimising the need for continuous maintenance (USEPA, 2000).

Typology of recovery and/or improvement of habitats and ecosystems

Many studies in scientific literature report different typologies of recovery in aquatic habitats and ecosystems (see, e.g., Fonseca et al., 2002; Simenstad et al., 2006; Elliott et al., 2007; Bekkby et al., 2020; De Wit et al., 2020). The term "recovery" implies that a system will return to a previous condition after being in a degraded or disrupted one. The return to the original state will be with (active recovery) or without (passive/natural recovery) human interventions. As reported by USEPA (2000), restoring the original hydrological regime of wetlands may be enough to re-establish, with time, the native flora and fauna communities.

Eco-engineering is increasingly used to recreate and restore ecosystems degraded by previous human activities by two types of approaches. The Type A approach that consists on restoring the hydrological processes and physico-chemical conditions necessary to a natural Self-improving of ecological structure and functioning, and the Type B approach that consists on a direct intervention on biota with transplanting actions (Elliott et al., 2016).

Methods for monitoring the impact of the project

Design of monitoring schemes occurs at the planning stage of the restoration project to ensure that the project's goals, objectives and indicators are measured. Chosen parameters and tools for monitoring activities depend on the conditions that the project is going to restore. Monitoring plans should be feasible in terms of costs and technologies, and should always provide relevant information to meet the project goals. The monitoring results indicate whether goals are being achieved and if it is necessary to modify actions of restoration by adaptive management. Since restoration efforts may not proceed exactly as planned, adapting a project to at least some changes or new information should be considered as normal (USEPA, 2000).

Application of the methodology to LIFE Lagoon Refresh

Project area, project site, and area of interventions

The project area is located in the northern Venice Lagoon in Italy (NATURA 2000 network codes: Sites for Community Importance, SCI, IT3250031 and Special Protection Area, SPA, IT3250046) (**Figure 1**). The surface of the SCI is 20,365 ha with 18% of the surface characterised by habitat 1,150*, 10% of habitat 1,420 (Mediterranean and thermo-Atlantic halophilous scrubs, *Sarcocornetea fruticosi*) and 8% of habitat 1,140 (Mudflats and sandflats not covered by seawater at low tide). The NATURA 2000 Standard Data Form describes this SCI as an environment characterised by salt marshes, tidal flats, channels, and river mouths with large portions occupied by typical Venetian fish farms. More than 330 species of birds are recorded in the Venice Lagoon and 66 are included in Annex I of Birds Directive (2009/147/EC), 25 of them are documented in the SCI of the northern Venice Lagoon (Bon et al., 2004). The total extension of reedbed in the SCI is of 34 ha and greater extension is close to the Dese river mouth.

The Project Site (**Figure 1**, see red line) has an extension of 1,900 ha and is located in Trezze area from Ca' Zane site to Santa Cristina Island. The Project Site falls into two of the twelve natural water bodies of the Venice Lagoon, identified in the WFD context: EC "Palude Maggiore" and PC1 "Dese," being the first as an euhaline waterbody (average salinity >30) and the latter as a polyhaline waterbody (average salinity 20–30). The freshwater flow from the watershed to the Venice Lagoon is about 34.5 m^3/s for the whole lagoon, and just about 17 m^3/s for the northern lagoon. In this area, the socio economic activities are fishing, hunting, and tourism.

The Area of Interventions (**Figure 2**, see yellow line) is about 70 ha and it is delimited by Sile river in the north, Valle Cesaro in the west, Valle Lanzoni in the east and Valle Ca' Zane in the south. In this area, along the Sile river embankment, a spillway is present. During flood events (about a dozen per year), thousands of cubic metre of freshwater spill from the river into the lagoon, without a buffer zone able to reduce nutrient load.

Hunting activities in the Venice Lagoon are very intense and there are about 600 hunting posts; three of them are placed within the Intervention Area.

The policies and socio economic context

In the Venice Lagoon, the environmental restoration has a long story. The idea of a basin-scale policy (not extended to the mainland) was contained in the "Special law for Venice" (Italian government Law no. 171/1973). During the 20th century, human activities have endangered two of the key habitats of the lagoon, the salt marshes and the aquatic angiosperm beds (Tagliapietra et al., 2018). While environmental conservation and restoration programmes (such as, Morphological plan of the Venice Lagoon; LIFE SeResto, LIFE12 NAT/IT/000331; LIFE VIMINE, LIFE12 NAT/IT/001122) have been put in place for the just cited endangered habitats, almost nothing has been done to recreate the lost salinity gradient. Indeed, LIFE Lagoon Refresh is the first project aimed at restoring salinity gradient and reedbeds in the Venice Lagoon.

The River Basin Management Plans of Eastern Alps District consider as a measure the general idea of restoration of salinity gradient and of ecotonal environments, therefore, as reported in the methodological approach, the project could be considered as a pilot example to replicate in other sites. Before investing in restoration, evidence of potential for long-term conservation management of the site was assessed. Indeed, the developed hydraulic and morphological works are environmental-friendly, having a very low maintenance. Moreover, the principal public authorities, responsible for the

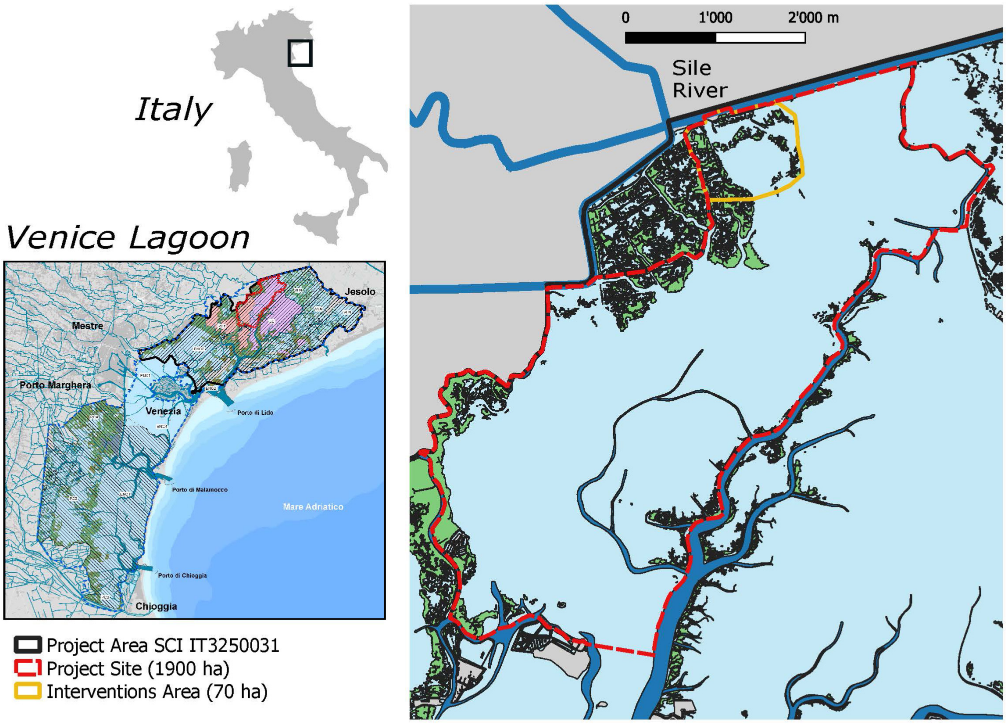

FIGURE 1
Project area, project site, and interventions area of the life lagoon refresh project.

management and safeguard of the Venice Lagoon, are partners of the project and agreed to pursuit their efforts in the area still after the project lifecycle.

Stakeholders' analysis identified a large spectrum of categories potentially interested by the project: national and local authorities, Reclamation Consortia, fishermen's, and hunters' organisations and people attending the northern Venice Lagoon. A Regional Environmental Impact Study was carried out for the Project. The District Authority of the Eastern Alps and Regional Directorate for Environmental Assessments played a fundamental role in the approval process. The environmental regulations they referred to assess the compliance of the project were the WFD, Habitat and Birds Directives, respectively, and all of them refer to river and lagoon environments. Therefore, it was necessary to verify the compliance with minimum in-stream flow of the Water Protection Plan of Veneto Region in accordance with the environmental objectives for rivers defined by WFD. The Sile river waters are also used for drinking and for irrigation purposes in agriculture. Therefore, it was necessary to verify with Water Authority and Reclamation Consortium that the flow of 1,000 l/s would not compromise those uses and the diversion would not worsen salt intrusion.

In the Venice Lagoon, fishing and hunting activities are regulated by a Regional fishing plan and a wildlife-hunting plan, respectively. Any modifications in fishing and hunting rules must be discussed and coordinated with Regional competent institutions.

In the northern Venice Lagoon, there are about twenty-two fishermen's and hunters' organisations for a total of about 4,000 people, therefore sharing the project and its aims was essential. In this context, a kind of wasp-waist strategy was adopted as following. In the planning stages, the project was discussed with two/three key representatives of fishermen and hunters, highly sensitive to environmental issues. They introduced LIFE Lagoon Refresh referents to the presidents of the associations, and a collaboration was established to involve the government boards of the associations. LIFE Lagoon Refresh staff met the boards to explain them the project, the goals, the conservative actions and the intention to involve fishermen and hunters in specific concrete actions of the project, namely in transplantations of reeds and aquatic plants. In this way, the project met consensus among them by working together, and it reached a very important goal, that is to relocate the three hunting posts outside of the project area of interventions.

Restoration goals and expected results

The effective condition of natural habitats in the project area before rivers' diversions could not be known in details, as the anthropic management of the Venice Lagoon and of

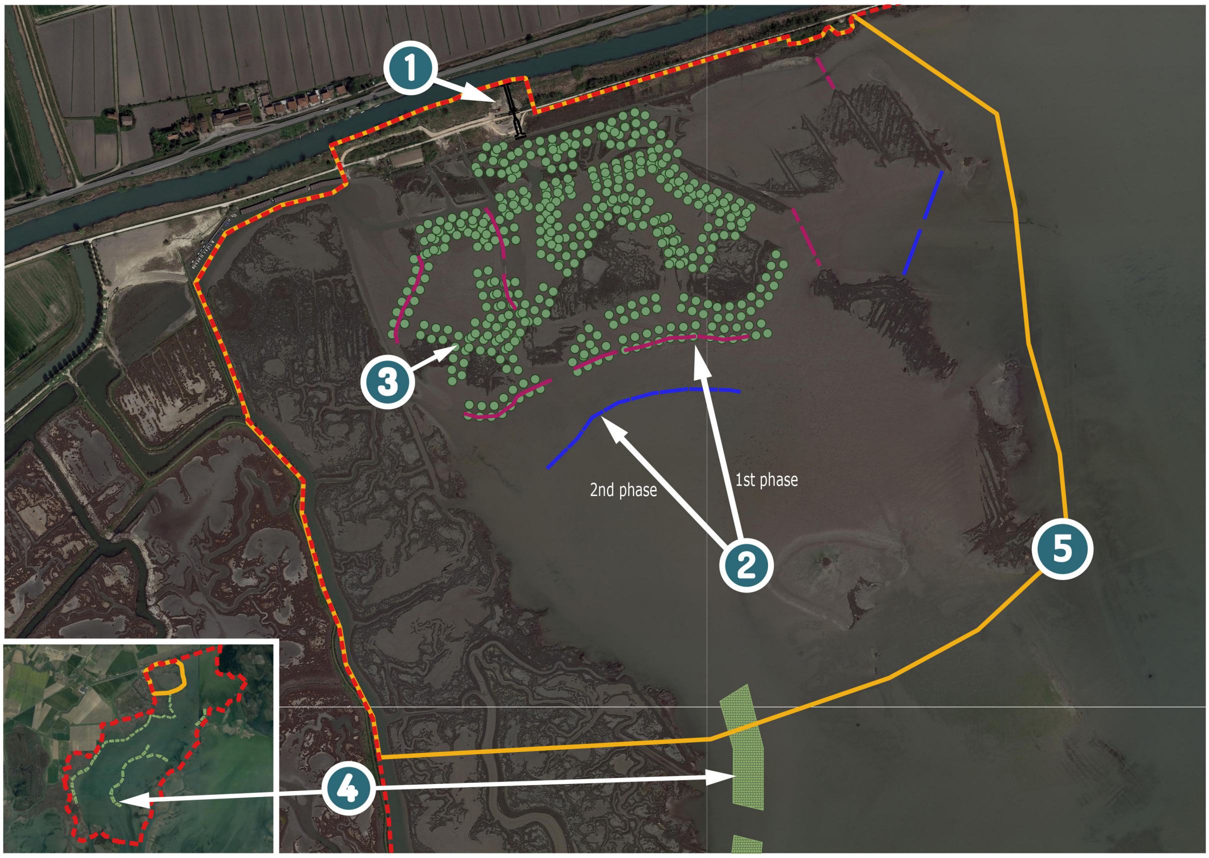

FIGURE 2
Overall picture of the identified conservation actions of the Project. (1) Hydraulic works; (2) morphological works; (3) *P. australis* transplantation; (4) aquatic angiosperm transplantation; (5) area of reduction of hunting and fishing pressure.

its watershed started centuries ago. As pragmatically reported by Lewis (1990), in such cases it is not necessary to know the original condition of the natural habitat, but only to know which habitat type was there, and to refer to the same general habitat type. Some historical maps attest the massive presence of a mixed habitat of reedbed/salt marshes/mud flats (see, e.g., D'Alpaos, 2010; D'Alpaos and Carniello, 2010). Nowadays, a residual fraction of that mosaic of habitats is present in the areas close to the small rivers still flowing into the lagoon. The LIFE Lagoon Refresh project has not the ambition to restore the original Sile river mouth before its diversion, but to restore the lagoon oligohaline habitats, by the creation of a new freshwater input. The low salinity and morphological variations would make the environment more suitable for the growing of reedbed and it could provide valuable and diversified ecosystem services, such as the purification of the water by reducing the degree of eutrophication with, consequently, the improvement of benthic biocenosis. Moreover, there will be achievements of the improvement of the conservation status of bird species that use the reed environment during winter period and/or for breeding, foraging or nesting, as well as the increase of the presence of fish species attracted by lower salinity environments. Finally, an improvement of the conservation degree of habitat 1,150*, according to Habitat Directive, and a restore of physical, chemical, morphological, and ecological conditions are expected, too.

In estuarine and coastal ecosystems, Borja et al. (2010) reported that, in some cases, recoveries can take <5 years, whilst the full recovery from over a century of degradation can take a minimum of 15–25 years for attain the original biotic composition and diversity. Despite of a lack of studies that provide the timing for recovery, LIFE Lagoon Refresh proposal provided hypothesis for the necessary time to reach the expected results. Indeed, the salinity gradient is expected to be attained within project duration time, once hydraulic and morphological works are completed and regime water discharge reached, whilst habitat, ecological and target bird species outcomes are expected within 5 years after the end of the project. The response of target fish species (e.g., *Pomatoschistus canestrinii*) to the restoration of the salt gradient should be rapid and expected within project duration time (Scapin et al., 2019a). On the other hand, the outcomes of the fish assemblages to the restoration of aquatic habitats are expected to take longer than the project time (Scapin et al., 2019b).

Typology of recovery

The LIFE Lagoon Refresh project started in 2017 and lasted 5 years. It considered two different types of conservation actions, following the approaches by Elliott et al. (2016). Two actions for the recovery of the salinity gradient (Type A):

(1) Diversion of a freshwater flow (1,000 l/s) from the Sile river into the lagoon.
(2) Restoration of the intertidal morphology to slow down the fresh water diffusion and sustain the reed development.

In addition, two actions that directly act on the ecosystem (Type B):

(3) Transplanting of *P. australis*.
(4) Transplanting of aquatic angiosperms.

To obtain the greatest chances of success for restoration, the strategy and choices for transplantation actions are consistent with Bekkby et al. (2020), and in particular are:

(1) The choice of the donor and recipient sites: to ensure that the restoration site has suitable physical conditions and biological characteristics, as similar as possible to that of the donor site. In transplantation activities, donor site was chosen in an area of the Venice Lagoon with similar characteristics to intervention area.
(2) The identification of the best transplantation methodology: all transplantations activities are carried out manually preferring a widespread transplant of small clumps.
(3) The specific features of the selected species, *P. australis,* and most of the selected angiosperm species are fast growing species with high reproductive outputs; generally, they have high dispersal, connectivity and number of propagules.

Eco-engineering conservation measures

LIFE Lagoon Refresh is a project of active ecological restoration by using *in situ* eco-engineering. In this case, it was not necessary to remove the stressors of hydrological and physical alterations, but anthropogenic interventions were considered to be necessary to restore physical, chemical, and ecological conditions. To achieve physical expected results, the proposed interventions included the diversion of a freshwater flow from the Sile river into the lagoon, and the creation of an intertidal morphology properly arranged to slow down the freshwater dispersion. Proposed measures to achieve habitat, ecological and species results were: the restoration of the intertidal morphology to favour the reed development; the planting of clumps and rhizomes of *P. australis*; the transplantation of small clumps of aquatic angiosperm species; the implementation of restricting rules to contain the hunting and fishing pressure. **Figure 2** reports the overall picture of the identified conservation actions.

Modelling tools

One of the key elements of the project was the prediction (forecasting) of the optimal freshwater discharge necessary to achieve the expected goal of restoring the salinity gradient. Nevertheless, for the objectives related to the conservation of habitats, a qualitative assessment based on a comparison with similar habitats was enough, whilst for the prediction of the expected variations in terms of salinity, a quantitative approach was essential. In particular, to verify the successful achievement of the project goals, it was necessary to setup, with a proper planning and implementation, a numerical model suitable for operating as a forecasting and hindcasting tool. Indeed, it allowed setting quantitatively the project objectives and it was functional to predict the expected results in terms of variations in space and time of salinity. It also allowed verifying, in analysis mode (hindcasting), the effects of the project actions, integrating modelling results with monitoring data collected as part of the project.

In the writing phase of the proposal, the modelling tool was applied to optimise the design choices related to the construction of the freshwater intake structure and for the realisation of the morphological structures.

The numerical simulations were carried out using the finite element numerical model 2DEF validated in the Venice Lagoon (Viero and Defina, 2016). The model was also applied in 3D baroclinic mode (3DEF model), as it is mostly suitable for simulating salinity transport and mixing in very shallow tidal environments.

According to the project objectives of salinity gradient restoration, simulations were carried out to compare the effects of different discharges of the freshwater input, starting from 300 l/s up to 1,000 l/s, as well as different morphological configurations, differentiated per extension, location and height of the structures designed to slowdown the dispersion of freshwater (**Figure 3**). The different configurations were compared in terms of percentage of salinity variation at a number of checkpoints near and with increasing distances from the intervention area.

Hydraulic works

The hydraulic works were planned considering the requirements and restrictions as following. Technical feasibility related to hydraulic risks of the Sile river; limitation due to

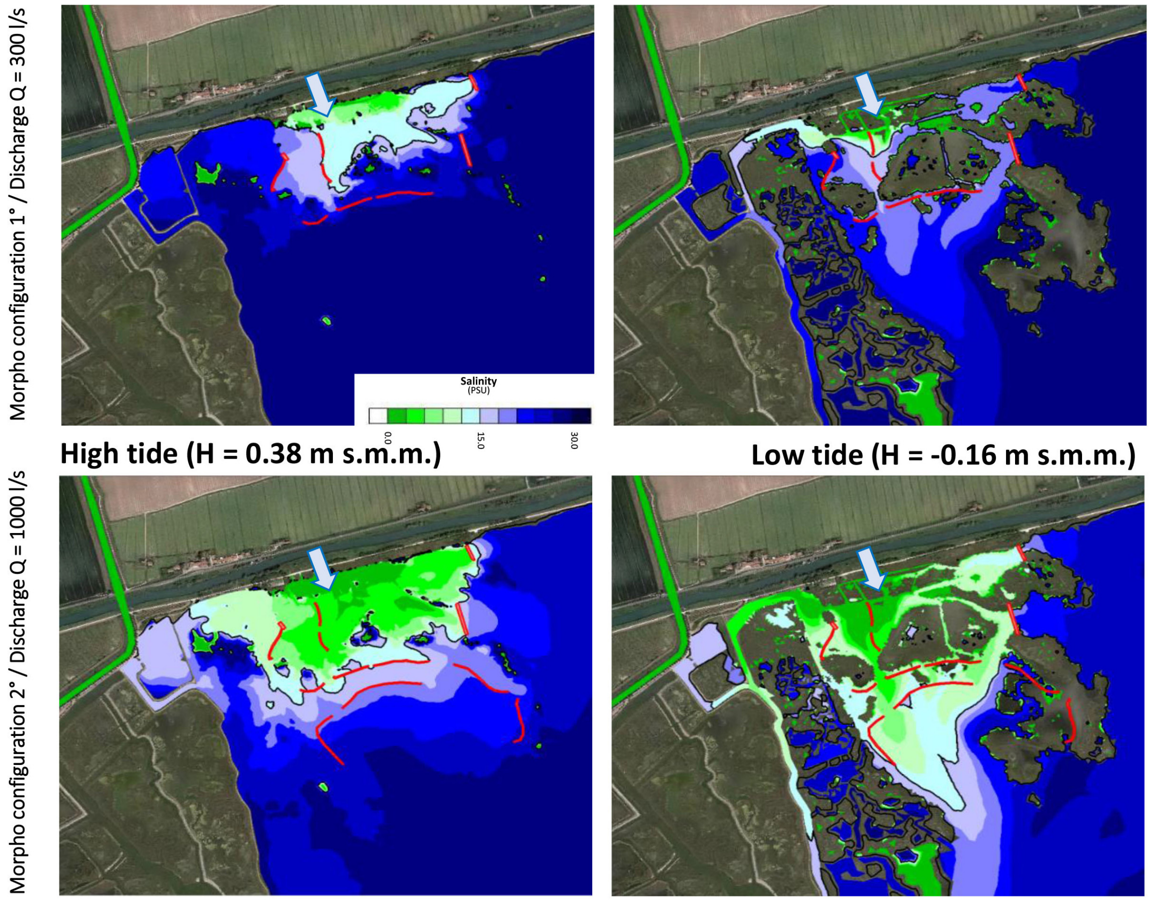

FIGURE 3
Maps of salinity distribution in the surface layer (0.08 m above sea level, a.s.l.) with simulations of freshwater displacement in the design phase. **Top**: with an inflow of 300 l/s and first phase of morphological works. **Bottom**: with an inflow of 1,000 l/s and second phase of morphological works.

other downstream freshwater uses; ensure in the long-term of the designed discharge (including low-maintenance effort); flexibility in regulating the discharge; no energy consumption; integration with the landscape.

The hydraulic works included three elements: (i) a linear channel for intake from the Sile river with a length of 40 m and width of 3 m; (ii) a crossing of the embankment, made by two parallel pipes with a diameter of 0.8 m; (iii) an inflow channel in the lagoon with a length of 20 m, a width of 4 m and two non-return valves at the beginning of the channel (Figure 4).

The freshwater from the Sile river to the lagoon has flowed since May 2020 by gravity according to the differences between the river and the tidal level in the lagoon, and it is adjustable *via* two sluice gates. The flow was gradually increased starting from 300 to 1000 l/s in February 2021. The structure is equipped with two flow metres and measured data are accessible in remotely real time. The low energy needed to make them work is guaranteed by solar panels. The visible structures are covered with bricks recalling typical rural houses.

Morphological works

The morphological works were planned, considering the low bathymetry and fragility of the project area, as well as the following requirements: effectiveness in slowing down the dispersion of freshwater introduced into the lagoon; establishment of a suitable substrate for the reedbed development; all constructions must be carried out manually; no dredging of temporary channels; adaptive management through phases of realisation.

Materials and technical solutions for morphological structures were investigated, considering the characteristics of the bottom of the lagoon, the expected hydrodynamic forcing derived by modelling results, and the function of reed transplanting. Long time was spent investigating solution available on the market, in particular for biodegradable materials. The final choice was to use light and biodegradable materials (coconut fibbers and jute), with modular bags placed manually from small boats, without the need to dredge channels necessary in case of heavy equipment. The works were divided

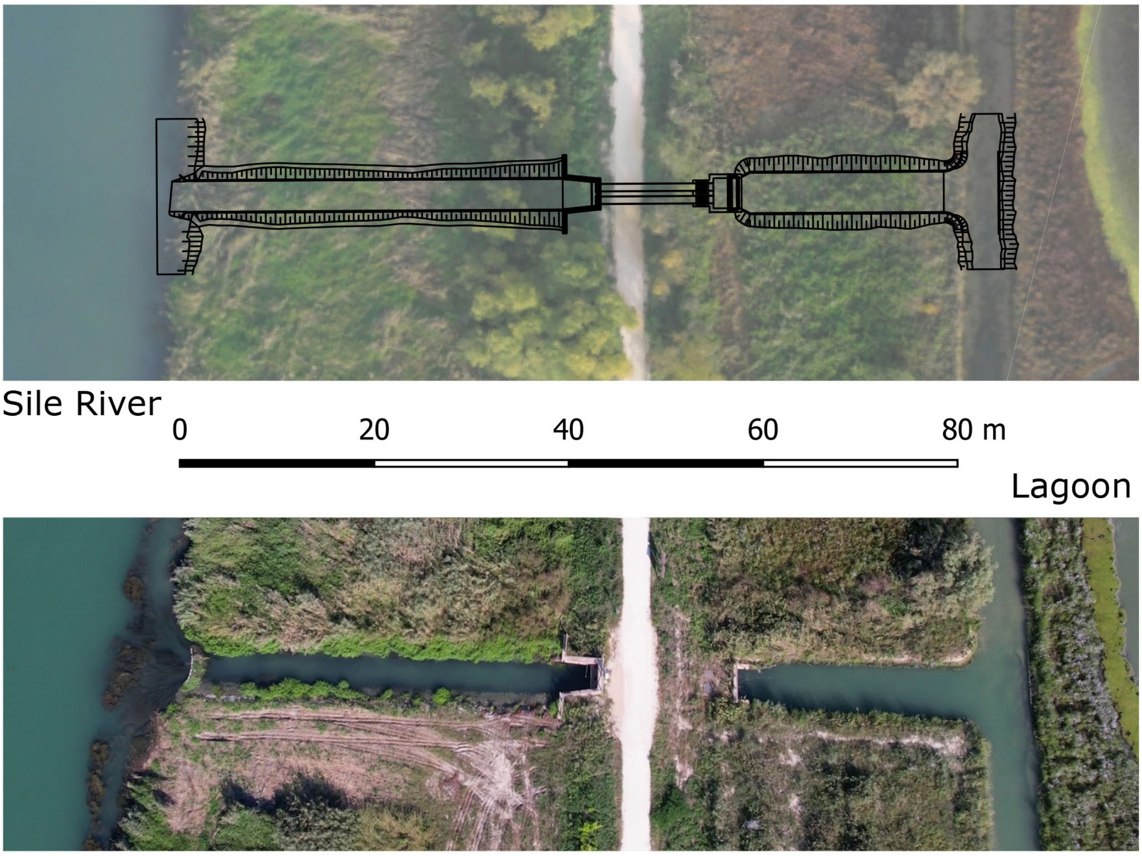

FIGURE 4
Hydraulic works. **Top**: executive design; **bottom**: completed hydraulic works.

into two lines at growing distance from the freshwater input. Considering the novelty of the structures, it was decided to carry out the morphological works in two phases, to allow an adaptive management strategy. Due to the large use of biodegradable materials (chosen as the most environmental-friendly solution) and the risk of bag deterioration before having fully performed their function of slowing down the dispersion of freshwater and of reedbed substrate, the second line of structures was realised about 1 year later, following the increase of the discharge up to 1,000 l/s. In the first phase, 775 m of linear structures were realised near to the freshwater input, with an elevation of approximately 0.10 m above sea level. In the second phase, 400 m of linear structure were realised and placed at greater distance from freshwater input. The second phase was realised starting from the results obtained by the first one in terms of consolidation, salinity monitoring and modelling results, and it was optimised to allow the establishment of suitable salinity conditions for the development of the reedbeds (**Figure 5**).

Measures to restore biological and ecological integrity

Once the conditions of water salinity and topography required to sustain the target ecosystem were met, approx. 2,500 small clumps and rhizomes of *P. australis* were transplanted to accelerate the natural expanding process of reedbed. The transplant activities were carried out by fishermen and hunters trained during the project. All activities were conducted manually with a very low impact to donor and transplant sites. Clumps of about 10–15 cm in diameter were explanted from healthy and well developed reedbeds near the project site, paying attention to not disturb fauna, especially nesting birds. Reed clumps were transplanted in areas characterised by low salinity (less than 12) and water level higher than −0.20 above sea level, in a portion of the project site close to the freshwater input, both along the margins of the existing salt marshes and on biodegradable bags (**Figure 6**).

Aquatic angiosperm transplantations started at the end of hydraulic and morphological works. To define the

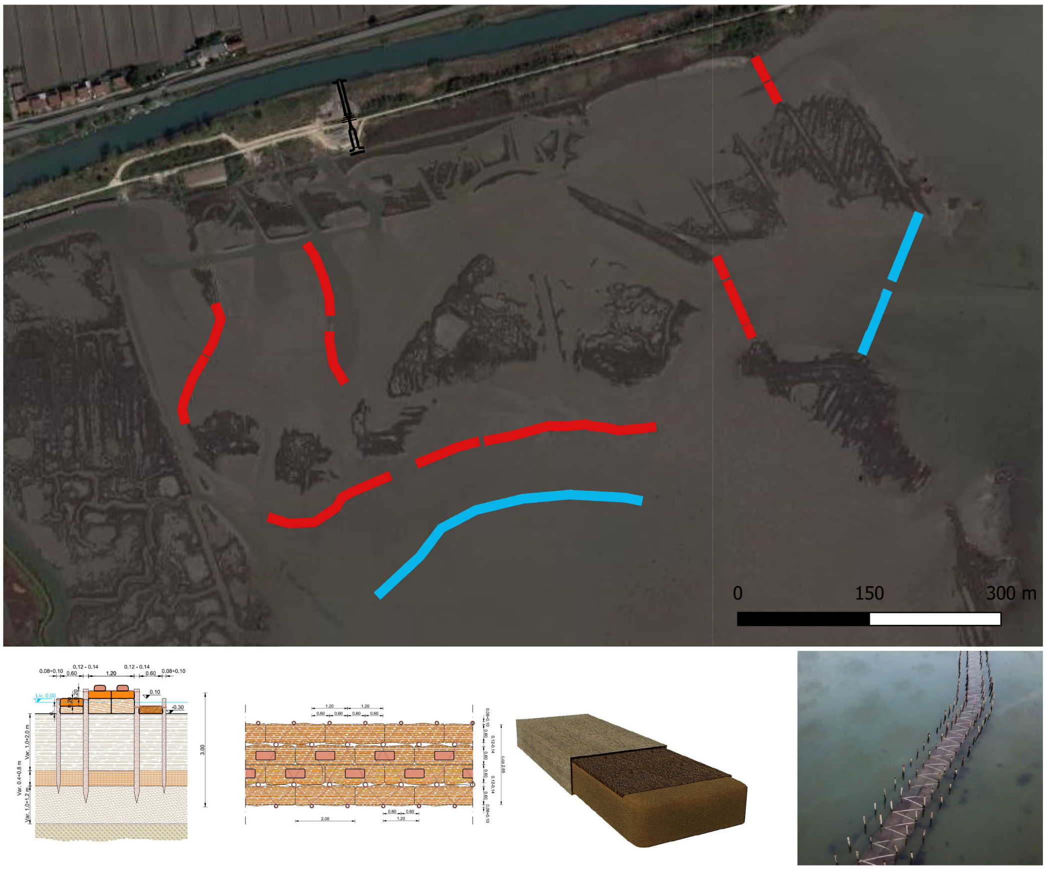

FIGURE 5
Morphological works. **Top**: in red first phase and in blue second phase. **Bottom**: executive design of morphological works, biodegradable module and frame of completed morphological works.

most suitable transplantation techniques and seasons, the experience gained in the LIFE SeResto project was taken into account (Sfriso et al., 2021). Small clumps (15–20 cm) of *Ruppia cirrhosa, Zostera noltei*, and *Zostera marina* were transplanted in the whole project site for a total of approx. 2,000 clumps. As well as for reedbed, angiosperm transplantations were carried out by fishermen and hunters trained during the project, and all activities were conducted manually with a very low impact to donor and transplant sites (**Figure 7**).

Monitor of achievement of project's objectives and goals

To verify the effects of measures, a detailed monitoring plan was scheduled in advance, at the planning stage of the project, to ensure that goals, objectives, and selected indicators would have been measurable. The experimental design included indicators necessary to assess the site condition prior to project initiation (baseline monitoring) and after project implementation to evaluate whether restoration actions met the project's expected results.

Restoration of salinity gradient

As saline gradient restoring is the main goal of the LIFE Lagoon Refresh project, the monitoring strategy aimed at capturing its changes, considering interactions between different hydrological and morphological processes, such as the modification of freshwater discharge, the effect of morphological works, tidal regime, exchanges with sea, etc. To assess whether hydraulic and morphological works were meeting the salinity expected results, a precise quantitative analysis of salinity with adequate resolution in time and space was adopted. Therefore, a combination of environmental monitoring and numerical modelling was applied. Characterisation in time and space of salinity variations, performed before and after the conservative actions, was obtained by the integration of three different tools: moored salinity probes that allow the acquisition, in fixed positions, of continuous measured data; field campaigns with

FIGURE 6
Reedbed (*P. australis*) transplantations in mudflat **(A)** and in biodegradable module **(B)**.

conductivity-temperature-depth (CTD) measures profilers that allowed the acquisition of instantaneous/spatially distributed measured data; implementation of numerical modelling that allowed simulation of modelled data with variation in space and time.

As planned, the restoration of salinity gradient was reached in the intervention area of 70 ha. Indeed, starting from >30 (annual mean salinity before project) at the whole area, the salinity has resulted less than 5, in 5 ha; less than 15, in 25 ha; and less than 25, in 70 ha after the interventions (Feola et al., 2022).

Habitat restoration

The assessment of habitat quality, according to the Habitat Directive requirements, is based on the criteria of "habitat structures" and "habitat functions." To assess habitat 1,150* structure, the salinity gradient was considered, as well as the eutrophication degree, evaluated by transitional water quality index (Giordani et al., 2009; Bonometto et al., 2022) and the mapping of submerged angiosperm vegetation. To assess functions, the ecological quality status improvement of macroinvertebrate, fish fauna and macrophyte communities were assessed, as well as water and sediment parameters, as reported in Ecological status improvement.

The period to assess these results was set within 5 years after the end of the project and monitoring activities are still ongoing. Currently the result concerning salinity gradient was achieved (Feola et al., 2022), and the first outcomes of fish fauna assessments indicated a quite positive response (see Species increasing). Based on expectations, the other indicators for habitat structures and functions will take a longer time to respond to the environmental changes. So, part of one of the objectives of the project, which was the consolidation and restoration of 1,250 ha of habitat 1,150* (34% of habitat area within SCI IT3250031) to "B" conservation status (corresponding to "good conservation" according to Habitat Directive) comprising 30% part currently in a "C" status (corresponding to "average or reduced conservation" according to Habitat Directive), was achieved.

The monitoring plan also provided habitat halophyte and reedbed mapping *ante* intervention and after the conclusion of hydraulic and morphologic works and *P. australis* transplantations. The *post operam* monitoring of halophyte and reedbed will last several years. The mapping activities include a combination of field monitoring and drone surveys. Expected results are the creation of reedbed on an area of approximately 20 ha and monitoring activities are still ongoing.

Ecological status improvement

For the ecological status assessment, protocols, defined by the Italian law (Ministerial Decree no. 260/2010) in agreement with the WFD, were applied. Biological Quality Elements (BQEs), such as macroalgae, aquatic angiosperms, macroinvertebrates, and fish fauna were monitored in addition to physico-chemical and hydromorphological quality elements that support the ecological status classification, by confirming or not the assessment provided by the BQEs.

A before-after monitoring strategy was adopted for all the quality elements (ecological, physico-chemical, and hydromorphological) at two spatial scales: at a local scale in the intervention area and at a larger scale in the project area. At larger scale, the monitoring network of the project was also integrated as part of the WFD monitoring network in the Venice Lagoon. Monitoring activities are still ongoing and results are expected within 5 years after the end of the project.

Species increasing

To monitor birds, especially those included in Annex I of Birds Directive, a diversified approach was adopted, considering the different species (migratory, wintering, and breeding) and the annual cycle. Therefore, three different monitoring activities included: (i) abundance detecting of passerines; (ii) total *census* of aquatic birds; (iii) *census* of *Botaurus stellaris* through sunset surveys (Luchetta et al., 2019).

Expected results regard specifically the increase of bird species typical of reeds, in particular *Phalacrocorax pygmeus, B. stellaris, Ardea purpurea, Ixobrychus minutus, Circus aeruginosus, Circus cyaneus,* and *Alcedo atthis*, with progressive structuring of the community.

Fish fauna monitoring aimed at assessing the ecological quality status of the community, as well as the presence of *P. canestrinii*, and other fish fauna species of commercial interest, such as *Dicentrarchus labrax, Anguilla anguilla*, *Chelon*

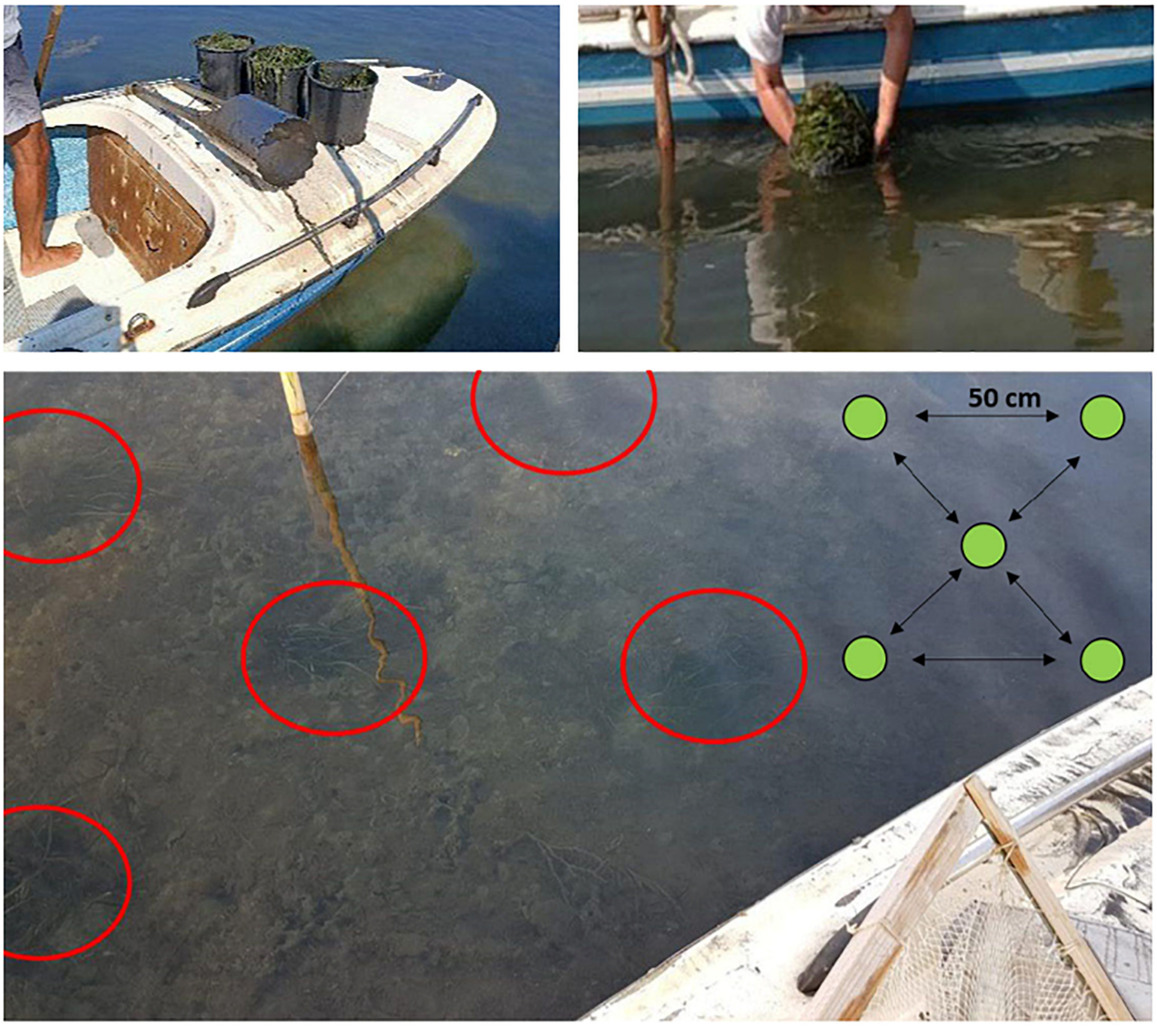

FIGURE 7
Aquatic angiosperm transplantation **(top)**. Scheme of transplantation **(bottom)**.

spp., *Atherina boyeri*, *Platichthys flesus*, and other species. Monitoring surveys were carried out twice a year (spring and autumn) for the entire duration of the project, by seine netting and by "bertovelli" nets before and after interventions.

A predicting model applied to the area assessed expected results (Scapin et al., 2019a). Very preliminary outcomes showed an increase of *P. canestrinii* from 0.1 ind/100 m^2 up to 20 ind/100 m^2 as expected by the project. Moreover, an increase of juveniles of commercial species, mostly mullets (*Chelon* spp.), was observed near the freshwater inflow.

Discussion

The application of the restoration project in the northern Venice Lagoon, LIFE Lagoon Refresh, resulted a clear case and real application of the purposed method, based on the collection of available theoretical indications for restoration projects and produced a methodological approach suitable for transitional waters. The main intervention realised in the Venice Lagoon from the second half of the 16th century was the diversion of main rivers. The reduction of hundreds of cubic metres per second of freshwater that flowed into the lagoon resulted in an increase of salinity and consequently in a heavy modification of its habitats and ecology. LIFE Lagoon Refresh is an active ecological restoration project that adopts an *in situ* eco-engineering approach aimed at recovering, in the northern Venice Lagoon, the salinity gradient, and at re-establishing the physical, chemical and biological processes and, subsequently, the ecotonal environment characterised by large intertidal areas vegetated by reeds *P. australis*. In this work, the strategy of the project and the foreseen conservation actions highlighted the integration of multidisciplinary knowledge on biodiversity and ecosystem functioning, hydrological and morphological aspects, legislation, as well as socio-economic aspects concerning the involvement of local stakeholders. Each restoration goal was clearly converted into specific objectives and indicators. Starting from the status assessments, as required by European Directives, such as Habitat, Birds, and WFD directives, same indicators were used to properly forecast outcomes. In this context, the desired state to be achieved was assessed by objective, as well as intercalibrated methods that are internationally recognised. Moreover, modelling applications resulted suitable and very useful to provide reasonable and quantitative outcomes to achieve. In addition, times to meet the objectives were also scheduled. Finally, indicators were established to assess progresses during the project, and to eventually adopt mitigation interventions.

The conservation actions were identified through a participatory process to reach the presented goals. Indeed, the Venice Lagoon is a very complex area concerning policies and socioeconomic contexts, from national to local authorities, associations, fishermen, hunters, and people attending the area. Therefore, meeting the agreement of the numerous stakeholders was one of the most important step for the realisation of the project. The key to success was to recognise the expectations and interest of all of them, and directly involving them, as for example including fishermen and hunters in transplanting actions. Currently, as most stakeholders know and share the project objectives, they could be also the keeper and maintainer of them for the future. Moreover, also the partners of the project, as principal authorities of the area, were directly involved in the interventions, and they will be the owner and responsible of the works after the end of the project.

Conclusion remarks

The case study of LIFE Lagoon Refresh project showed the effectiveness of the multidisciplinary method depicted in this manuscript, which met the application of theoretical advice with a methodological approach. This is especially relevant for restoration of coastal lagoon habitats, which are highly productive ecosystems, rich in flora and fauna of conservation interest and, unfortunately, subjected to multiple threats that may endanger their quality status or existence.

As results, this method can be applied to several coastal lagoons in order to reach the desired state, starting from a robust assessment of environmental, policies and socioeconomic context, clearly defining the typology of recovery, identifying the best configuration of conservation actions, and assessing the impact of the project through an integrated monitoring plan. The study could be considered as an innovative pilot example of restoration strategy and application that can provide a baseline for future similar interventions.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

RB, AF, FC, and AB: conceptualization and writing—original draft preparation. AF, FC, EP, BM, AS, PF, and NB: investigation. AF: visualization. RB, AB, AS, ML, PP, and VV: resources, project administration, and funding acquisition. RB and AB: supervision. RB, AF, FC, EP, AS, PF, ML, PP, BM, NB, VV, LM, and AB: methodology, writing—review and editing the manuscript, and approved the submitted version.

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Conflict of interest

PP and BM were employed by IPROS Environmental Engineering s.r.l.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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