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Combining participatory and GIS-based multi-criteria decision analysis for salt marsh restoration and rebuilding planning in the Venice lagoon

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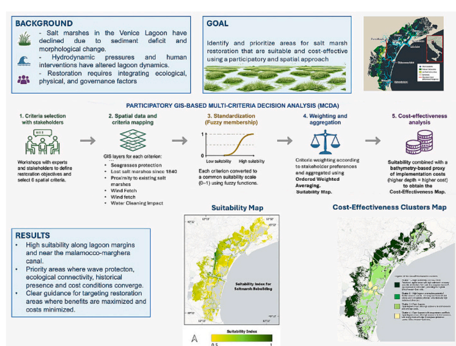
HIGHLIGHTS

- GIS-MCDA identified priority areas for salt marsh restoration in the Venice lagoon.
- Six spatial criteria were selected and refined through stakeholder input.
- Ordered Weighted Averaging captured different restoration risk attitudes.
- Cost-effectiveness mapping revealed trade-offs between suitability and cost.
- Key hotspots emerged near lagoon margins and the Malamocco-Marghera canal.

GRAPHICAL ABSTRACT



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ABSTRACT

The Venice Lagoon has experienced a long-term decline of salt marsh habitats due to sediment deficit, morphological deepening, increased hydrodynamic exposure, and human-induced alterations to lagoon processes. Identifying suitable locations for restoration is therefore a key challenge for lagoon management. This study applies a participatory GIS-based Multi-Criteria Decision Analysis (S-PMCA) to support the spatial prioritization of salt marsh restoration and rebuilding within the framework of the WaterLANDS and REST-COAST projects.

The analysis combined stakeholder knowledge with spatially explicit environmental information. An initial set of criteria was reviewed through a pre-workshop survey involving 21 stakeholders and subsequently refined during a workshop attended by 43 participants. The final analysis incorporated six spatial criteria: distance from canals, wind fetch, proximity to existing salt marshes, historical salt marsh loss, seagrass protection, and water quality. Criteria were transformed into standardized suitability layers and weighted according to stakeholder

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preferences. Distance from canals received the highest average importance weight (21.4/100), whereas water quality received the lowest (13.8/100).

Suitability maps were generated using an Ordered Weighted Averaging (OWA) approach and combined with a bathymetry-based proxy of restoration costs to perform a spatial cost-effectiveness assessment. Priority restoration areas were identified along lagoon margins and near the Malamocco–Marghera Canal, where wave attenuation potential, ecological connectivity, historical marsh presence, and favourable implementation conditions converge.

By combining stakeholder preferences with morphodynamic conditions, ecological factors, and implementation costs, this study supports the identification of restoration areas that are both feasible and strategically relevant in the Venice Lagoon.

1. Introduction

The Lagoon of Venice is one of the largest and most ecologically significant transitional coastal ecosystems in the Mediterranean (Tagliapietra et al., 2009, 2018). Located in the northern Adriatic Sea, it covers approximately 540 km^2 and is connected to the sea through three inlets (Lido, Malamocco, and Chioggia, see Fig. 1). The lagoon is shallow (mean depth ~1.2 m), microtidal, strongly influenced by semidiurnal tidal exchanges that regulate sediment transport, salinity gradients, and morphological dynamics (Molinaroli et al., 2009; Tagliapietra and Ghirardini, 2006), and characterized by a mosaic of salt marshes, mudflats, seagrass meadows, and artificial wetlands (Tagliapietra et al., 2018). Despite maintaining important natural features, the lagoon is a highly human-modified system and is recognized as a UNESCO World Heritage cultural landscape, reflecting centuries of interaction between environmental processes and socio-economic development (Trovo and Bruschi, 2025). Profound alterations in the lagoon's morphology resulted from a combination of anthropogenic and natural drivers. Although they began in previous centuries, during the twentieth century, major anthropogenic interventions profoundly altered lagoon hydrodynamics and sediment balance. The construction of jetties at the inlets, the excavation of deep navigation channels linking the Malamocco Inlet to

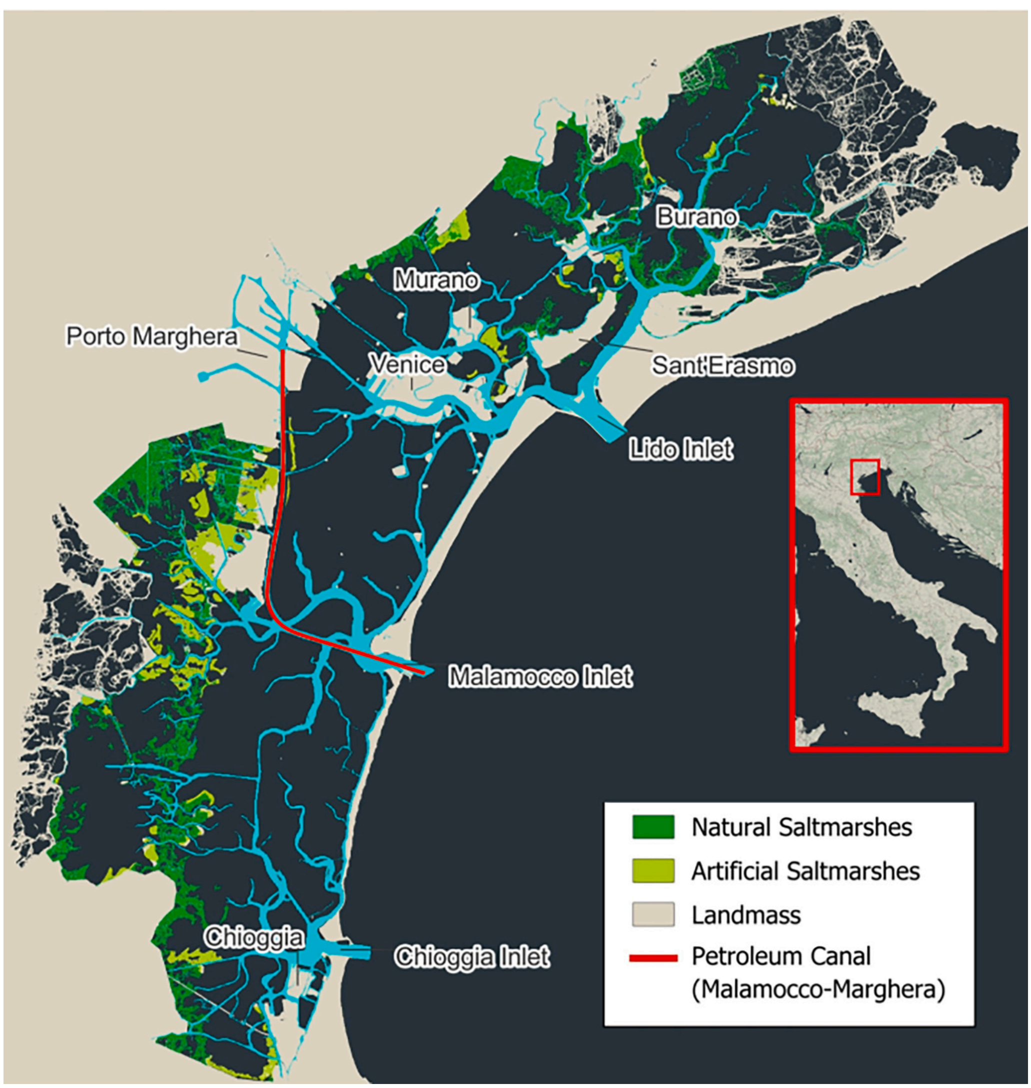

Fig. 1. The Venice Lagoon, its location within Italy as well as main locations, the 3 inlets, the main islands, the canals, the Malamocco-Marghera canal, artificial and natural salt marshes in 2023.

the mainland industrial area, land reclamation, and reduced freshwater inputs significantly modified circulation patterns and sediment fluxes (D'Alpaos, 2010; Bernstein and Montobbio, 2011). Human-induced land subsidence and the excavation of navigation channels between 1927 and 1970 initiated major changes, which were later compounded (1970–2002) by severe natural erosion intensified by sediment re-suspension associated with Manila clam harvesting (Sarretta et al., 2010).

Overall, the lagoon experienced a net sediment deficit of approximately 110 million cubic meters (Mm^3). The majority of this loss—around 70%—occurred between 1927 and 1970. A considerable share of sediment was removed through dredging operations and subsequently disposed of outside the lagoon system, either on land or offshore. In addition, an estimated 39 Mm^3 was eroded by tides corresponding to an average annual loss of about 0.5 Mm^3 (Sarretta et al., 2010).

Since the eighteenth century, the total surface of salt marshes has continuously declined (Carniello et al., 2009; L. D'Alpaos, 2010; Tommasini et al., 2019), with marked losses in the central lagoon and a progressive transition from intertidal to subtidal environments which increased from 88 km^2 in 1927 to 206 km^2 in 2002 (Sarretta et al., 2010). Historical reconstructions indicate that salt marsh extent decreased from approximately 180 km^2 in the early twentieth century to about 43 km^2 in recent years (Atlante della Laguna di Venezia, 2015; D'Alpaos, 2010).

More recently, the Mo.S.E. (Modulo Sperimentale Elettromeccanico) storm-surge barrier system, designed to protect Venice from high tides, has introduced additional hydrodynamic alterations since its first activation in October 2022 and with more than 150 closures performed over less than 4 years. By limiting storm-surge inflows, which contribute substantially to salt marsh sedimentation, the system may reduce sediment delivery to marsh platforms, potentially constraining their resilience to sea-level rise (Tognin et al., 2021).

The long-term reduction of salt marsh habitats and associated ecological functions underscores the need for spatially explicit restoration planning (Kazemi and Akinci, 2018; Boggia et al., 2018).

This study aims to support the spatial prioritization of salt marsh restoration in the Venice Lagoon through the application of a participatory and spatially explicit Multi-Criteria Decision Analysis (Greene et al., 2011) framework. In response to the long-term decline of the Venice salt marsh environment and the complex governance context that characterizes lagoon management, this analysis seeks to identify suitable areas for restoration and rebuilding by integrating biophysical, ecological and morphological criteria within a Geographic Information System (GIS) environment (Turner et al., 2000). By incorporating stakeholder input into the weighting and prioritization of spatial criteria, the approach ensures that diverse perspectives, management objectives, and local knowledge are explicitly considered (Marttunen et al., 2015). Furthermore, by coupling the resulting suitability assessment with a proxy of intervention costs, the analysis serves as a decision-support tool for the identification and prioritization of cost-effective restoration areas.

Given the ecological urgency and governance complexity, restoration planning in the Venice Lagoon is being advanced through the coordinated efforts of two complementary European initiatives: WaterLANDS and REST-COAST. Both projects are funded under the European Commission's Horizon 2020 Framework Programme within the call "*Building a low-carbon, climate resilient future*: *Research and innovation in support of the European Green Deal* (*H2020-LC-GD-2020*)" and share the overarching objective of restoring biodiversity and ecosystem services in coastal wetlands.

In the Venice Lagoon, WaterLANDS and REST-COAST operated as coordinated sister initiatives, aligning methodologies and engagement processes to avoid stakeholder fatigue, reduce duplication, and ensure coherence in data collection and decision-making. Within this cooperation, Ca' Foscari University of Venice (WaterLANDS) developed a GIS-Based Participatory Multi-Criteria Analysis (S-PMCA) to produce a suitability map for salt marsh restoration, coupled with cost proxies for spatial cost-effectiveness analysis, integrating biophysical, morphological, and socio-economic criteria with stakeholder preferences. In parallel, REST-COAST leveraged its institutional platform, the Venice CORE-PLAT (COastal REstoration PLATform), to organize workshops and surveys and facilitate dialogue among key stakeholders, including the Venice Lagoon Authority (formerly Provveditorato Interregionale per le Opere Pubbliche), the Municipality of Venice, the Metropolitan City of Venice, the Veneto Region, the Venice Port Authority, as well as other relevant public bodies, researchers, and local actors.

The rest of the paper is organized as follows: in Section 2, we provide a contextual framework for our analysis, outlining the objectives and methodologies employed. Section 3 presents the main results and maps. Section 4 is a discussion on the possible improvements and diversifications useful for other purposes using the same methodology and logic of this analysis. We conclude in Section 5, reflecting on the outcomes from the workshops and discussions with the stakeholders of the Venice CORE-PLAT, as well as the main conclusions drawn from this work.

2. Methodology

The central methodological question guiding this work is how spatial and participatory multi-criteria analysis (S-PMCA) can effectively support the identification and prioritization of cost-effective restoration areas in the Venice Lagoon under conditions of environmental degradation and institutional complexity. To structure the analysis, the following research questions are formulated: (i) which spatial criteria are considered most relevant by institutional stakeholders for prioritizing salt marsh restoration in the Venice Lagoon? and (ii) how the resulting S-PMCA suitability map can be combined with information currently available about restoration costs to derive a spatial description of cost-effectiveness to support the prioritization of future salt marsh restoration areas?

For the identification of relevant criteria for the MCDA our primary source was the "Piano Morfologico per il Recupero Morfologico e Ambientale della Laguna di Venezia" (i.e. Morphological Plan for the Environmental and Morphological Restoration of the Venice Lagoon, hereafter PMLV) whose update was released in 2021, integrated with the results of the most recent studies available. The PMLV also informed the operationalization of the criteria within the MCDA framework. Beyond guiding the selection of relevant criteria, it provided the conceptual basis for defining the suitability logic associated with each variable, including the identification of preferred conditions, threshold values, and transformation functions used to translate raw spatial data into standardized suitability scores.

The PMLV provides a strategic framework for addressing the lagoon's hydrodynamic, morphological, and ecological imbalances through structural and management interventions aimed at sediment retention, erosion control, morphological stabilization, ecological restoration, and improved environmental quality. Priority actions focus on protecting and rebuilding salt marshes and shallow flats, limiting sediment export toward major channels, restoring ecological functionality such as seagrass development, and regulating human pressures including navigation and aquaculture.

The PMLV, beyond guiding the selection of relevant criteria, provided the conceptual basis for defining the suitability logic associated with each variable, including the identification of preferred conditions, threshold values, and transformation functions used to translate raw spatial data into standardized suitability scores.

To translate the strategic priorities of the PMLV and stakeholder inputs into an operational decision framework, a Participatory Multi-Criteria Decision Analysis (PMCA) approach was employed.

PMCA engages stakeholders in a structured decision-making process, incorporating their diverse perspectives to assess the feasibility and preferences on a series of spatial criteria that are critical for reaching the goal.

Moreover, a GIS-Based Participatory Multi-Criteria Decision Analysis (S-PMCA) approach was implemented to evaluate and compare multiple alternatives (pixels) based on a set of criteria to reach a decision where a stakeholder group's preferences are required or desired. S-PMCA facilitates the identification of preferable pathways for salt marsh restoration, proposing ways forward that achieve a 'just transition' without significantly disadvantaging any group of stakeholders (Dean, 2022; Talley et al., 2016).

In a spatial context, the alternatives are identified as unitary areas (in our study the resolution was 100 m^2), corresponding to the universe of pixels of raster-based criterion maps within the boundaries of the Venice Lagoon. The outcome of this process is a map ranking the suitability of areas for salt marsh restoration. The S-PMCA approach was preferred, because:

(1) Stakeholder involvement was considered as a prerequisite for supporting decisions of competent institutions.
(2) A broad spectrum of decision criteria that range from social, to environmental aspects must be considered together with their spatial variability.
(3) The desired outcome should be geographically explicit to answer the question about where to implement restoration activities.

2.1. *The implementation steps of S-PMCA in Venice*

In this section, we will outline the sequence of steps for the implementation of the S-PMCA design adopted in the Venice Lagoon. Fig. 2 illustrates the whole process, which we will outline briefly here and elaborate further in the subsequent subsections.

The process began with the identification and outline of the research objective, in particular in this step we: i) defined the scope of the S-PMCA exercise, ii) identified and collected relevant criteria for achieving the scope of the S-PMCA mainly through the The Morphological Plan of the Lagoon (PMLV) and through meetings with experts, iii) defined the Area of Interest.

The next phase initiated the participatory process with the identification of relevant institutional stakeholders involved in the safeguard and restoration of the Venice Lagoon, carried out by REST-COAST, followed by the distribution of a pre-workshop survey to gather feedback on an initial set of spatial criteria. A total of 21 responses were received, confirming the relevance of the selected criteria, namely (1) distance from canals (wave protective function), (2) seagrass protection, (3) historical loss of salt marshes (since 1840), (4) proximity to existing salt marshes, and (5) wind fetch. Water quality was suggested by respondents as an additional criterion during the survey and was subsequently incorporated into the analysis using the Macrophyte Quality Index (Sfriso et al., 2024) as a proxy indicator. Once the criteria were established and agreed upon, a half-day stakeholder workshop was held on October 14, 2024, during which project objectives were presented and participants were engaged in the S-PMCA exercise by assigning relative importance weights to each criterion, distributing 100 points to reflect their priorities in identifying suitable restoration areas (the survey is available in SI.3). The workshop also included an afternoon session under the REST-COAST framework focused on adaptation planning, where participants worked in subgroups to discuss future visions, priority pathways, key strategies, and potential tipping points (the workshop program is available in SI.2).

Based on the importance weights collected during the workshop, we adopted an Ordered Weighted Averaging (OWA) operator (Yager, 1988; Malczewski, 2006) to aggregate the six standardized spatial criteria in the resulting Suitability map. This approach allows the exploration of alternative decision strategies by varying the degree of compensation among criteria, while maintaining constant stakeholder-derived importance weights. Moreover, to generate the Cost-Effectiveness Map, we applied the ISODATA clustering approach using two inputs: (i) the Suitability Map and (ii) a proxy for restoration costs based on sediment volume, estimated through bathymetry. The analysis produced four clusters, ranging from highly cost-effective areas to low cost-effectiveness. These maps were then presented in a second workshop, where stakeholders were invited to review and discuss the preliminary outcomes. During this session, we received additional feedback that led to some methodological adjustments, including improvements to the transformation functions. The results of the revisions were subsequently

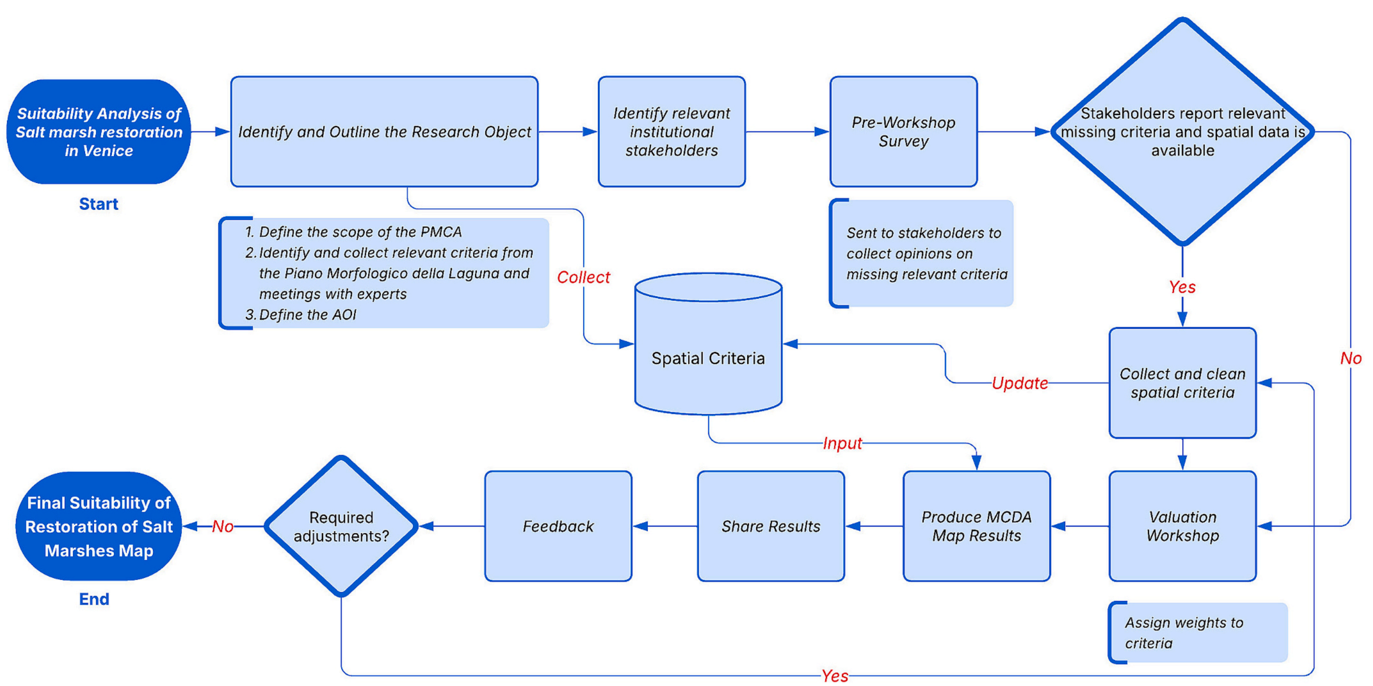

Fig. 2. The implementation flowchart of the S-PMCA approach adopted for the WATERlands and REST-COAST projects applied to the Venice Lagoon case.

shared with the Venice Lagoon Authority, the key institutional authority overseeing and coordinating salt marsh restoration and rebuilding efforts in the Venice Lagoon and the final set of maps was produced.

2.1.1. Stakeholder engagement

The stakeholder engagement process was mainly under the responsibility of the REST-COAST project. The participatory process took place through the design and operational implementation of the Coastal Restoration Platform (CORE-PLAT), conceived as a permanent multi-stakeholder platform to support decision-making and co-design processes for coastal restoration interventions to be implemented in the Venice lagoon through Nature-Based Solutions (NbS). The primary objective of the CORE-PLAT is to foster dialogue, collaboration, and knowledge exchange among the various stakeholders, in order to develop a shared vision for the lagoon's future and promote co-management and co-design processes for current and future restoration interventions.

The composition of the CORE-PLAT was defined through a systematic preliminary mapping of local stakeholders, which led to the initial identification of over 70 relevant actors, subsequently reduced to 38. They belong to both public and private sectors and include government authorities at various levels, such as research institutions and universities, environmental associations and NGOs, economic operators, civil society organizations, and local stakeholders with specific interest in safeguarding the lagoon ecosystem. This approach, initiated within already existing participatory processes (i.e. the Contract for the North of the Lagoon), is aimed at reducing the risk of stakeholder fatigue and strengthening the continuity of dialogue among actors already active in the area. This enabled the representation of a wide range of competences, interests, and levels of influence that characterize the governance of the Venice Lagoon, recognized as a complex socio-ecological system (Pernice et al., 2024).

The workshops and in-person meetings organized as part of CORE-PLAT showed a variable but overall significant level of participation. In particular, the joint REST-COAST–WaterLANDS workshop on S-PMCA enabled the structured integration of stakeholder preferences into the decision-making process, producing preliminary yet robust and shared results, which were subsequently translated into suitability and cost-effectiveness maps for restoration upscaling.

2.1.2. Workshop participants and facilitators

The 43 attendees of the stakeholder workshop were classified into 11 classes relevant for our analysis (see Fig. 3). According to these categories, the main representatives that attended the workshop were Government, policymakers & regulating actors which are defined as actors responsible for establishing and enforcing the regulatory and policy framework governing ecosystem use and management (25%), these actors are directly involved in the management of the Venice lagoon, and Knowledge actors (25%), coming mainly from CMCC, UNIPD, CORILA, UNIVE, but also including other universities and research institutions.

The third type of stakeholder were Restoration practitioners (14%), many of whom are actively involved in wetland restoration activities in the lagoon. Another significant group present at the workshop were Recreational wetland users (7%), many of whom are dedicated to organizing tours and sensitizing visitors to the environmental challenges that Venice faces, particularly those related to salt marsh degradation.

Smaller but also important groups included Art, cultural heritage & education actors (5%), Community and civil society actors (5%), and Community support/development agencies (5%), all of which play a role in fostering awareness and local participation in environmental restoration efforts. Wetland managers/environmental agencies (5%) and Financing actors (2%) were also present, contributing to discussions on resource management and exploring alternative funding opportunities for restoration projects.

2.1.3. Criteria

The spatial criteria included in the analysis were sourced from institutional datasets, publicly available geospatial databases, and project specific data sources relevant to the lagoon's morphology, hydrodynamics and ecological constraints, with a detailed list of all criteria and corresponding data sources provided in Supplementary Information

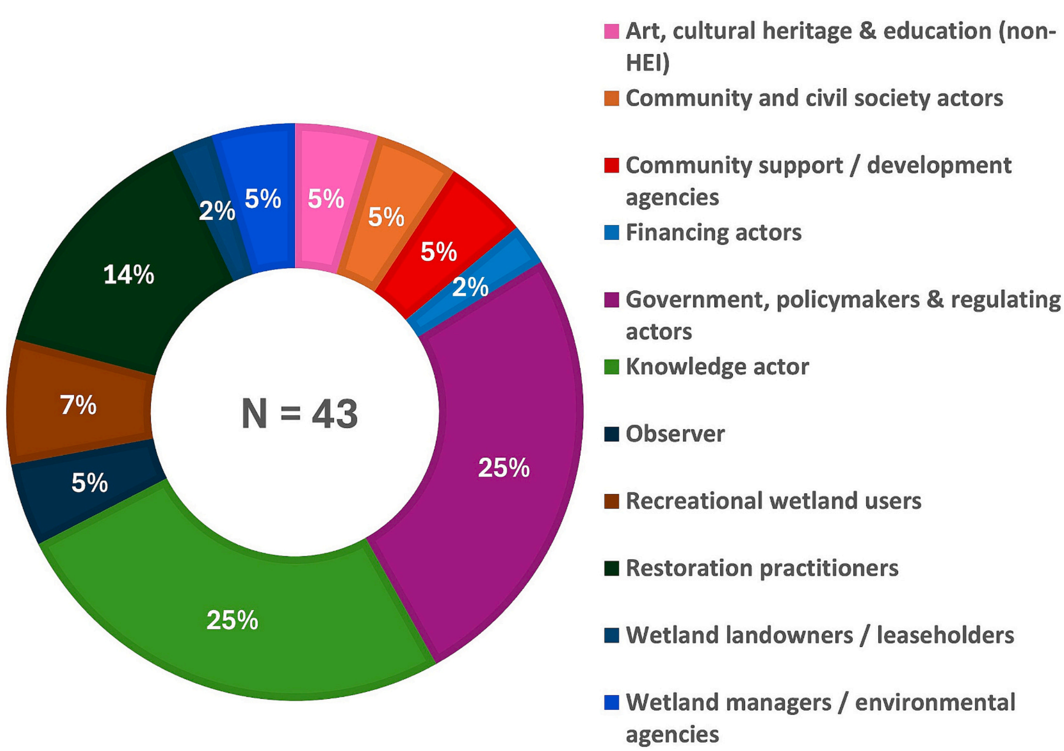

Fig. 3. Composition of workshop stakeholders' main role in the Venice Lagoon.

SI.1. The criteria are aligned with the objectives of the PMLV, particularly regarding habitat conservation, lagoon resilience, and ecological restoration. The final list of spatial criteria adopted for restoration suitability analysis is presented in Fig. 4. Prior to the Multi-Criteria Decision Analysis, all spatial layers underwent cleaning, harmonization, and preprocessing, carried out in QGIS 3.44 and R 4.5.3 depending on data structure and processing requirements. These steps included reprojection to a common coordinate reference system in meters, clipping to the study area, rasterization of vector datasets when necessary, alignment of spatial resolution and extent, removal of invalid or duplicated geometries, handling of missing values, and standardization of data formats. In some cases, continuous variables were derived from primary layers, such as distance-based indicators or morphodynamic metrics, and further transformed to ensure consistency across criteria.

For the Distance from Canals criterion, used to capture the wave protective function, a classification of main canals based on navigation rules, including vessel types and speed limits, was applied, with particular focus on the Malamocco-Marghera Canal, where protection is essential due to the intensive traffic of large ships heading to the Port of Venice (Tommasini et al., 2019; Scarpa et al., 2019). The seagrass criterion map was based on the most recent data by A. Sfriso in 2024, identifying gradients of biomass and areas of potential expansion, under the assumption that salt marshes should not be constructed in areas with existing seagrasses. A suitability criterion was also defined to prioritize areas where salt marshes were lost, by comparing current distributions (EUNIS 2023, detailed in Baptist et al., 2024) with historical maps. Proximity to existing salt marshes was also included to account for ecological connectivity. The wind fetch map was incorporated to capture wave exposure, which influences erosion, sediment stability, and long-term restoration success, with higher exposure areas considered more suitable to maximize wave attenuation and sediment retention functions (Finotello et al., 2020). Water quality was represented through the Macrophyte Quality Index, using an inverted transformation function to reflect the greater ecological benefits of restoration in more degraded waters (Vernberg, 1993).

The S-PMCA implementation was conducted using the TerrSet LiberaGIS software, specifically its Multi Criteria Evaluation module combined with a series of data processing routines stored within a single macro, enabling an efficient and repeatable procedure that was refined and rerun at each step of the participatory process. All criteria were converted into normalized suitability layers using value transformation functions (see Fig. 4) applied to the original values to reflect their contribution to restoration suitability (Yager, 2002), and stakeholder-derived weights collected during the workshop were applied to generate suitability maps. The Ordered Weighted Averaging operator (OWA) allowed us to explore how risk attitudes may affect the final results. The resulting suitability scores were then combined with bathymetry as a proxy for implementation costs using the clustering method ISODATA, assuming constant restoration techniques whereby deeper areas imply higher sediment requirements and therefore higher costs, to perform a spatial cost-effectiveness assessment.

2.1.4. Ordered weighted averaging implementation

The aggregation of the six standardized spatial criteria was performed using an Ordered Weighted Averaging (OWA) operator (Yager, 1988; Malczewski, 2006). OWA combines two sets of weights: (i) importance weights, derived from stakeholder preferences and assigned to each criterion, and (ii) ordered weights, applied after ranking criterion values at each pixel. The ordered weights determine the aggregation behaviour, enabling different configurations that reflect alternative risk attitudes (Makropoulos and Butler, 2006).

In this study, three aggregation configurations were tested (maps shown in SI.4 and SI.6): optimistic, balanced, and pessimistic. These configurations were implemented through different sets of ordered weights, which regulate the degree of compensation among criteria while keeping stakeholder-derived importance weights constant. The optimistic configuration assigns greater influence to higher ranked criterion values, allowing compensation among criteria and leading to more permissive suitability outcomes. The pessimistic configuration emphasizes lower ranked values, limiting compensation and producing more conservative results driven by the most constraining factors. The balanced configuration represents an intermediate strategy, where neither high nor low values dominate the aggregation process. This approach follows the standard application of OWA in spatial decision analysis, where alternative decision strategies can be explored without altering the relative importance of criteria (Mianabadi et al., 2014; Yager, 2009). For the final maps, the mean importance weights across stakeholders were used, while the balanced configuration was adopted for the ordered weights, as this combination captures the central tendency of stakeholder preferences while avoiding extreme decision attitudes.

3. Results

3.1. Elicitation of criteria importance

The analysis of the criteria weights for salt marsh restoration reveals interesting variations in stakeholder perceptions, as measured by the mean, standard deviation, and coefficient of variation across criteria. These weights were elicited by asking stakeholders to distribute 100 points among the six criteria according to their relative importance.

Fig. 5 presents the results of the criteria weighting. The criterion with the highest mean value was Distance from Canals (mean = 21.4), indicating that stakeholders placed significant importance on this factor when assessing potential sites for restoration. However, it also had the highest coefficient of variation (58%), reflecting substantial variability in the weight assigned to this criterion across respondents, potentially linked to the aforementioned trade-off. This suggests that while many stakeholders deemed close proximity to canals crucial, there was some disagreement about its relative importance with respect to the other criteria.

Wind Fetch, with a mean of 17.3, also showed a moderate degree of importance, but exhibited a somewhat lower variability than proximity to channels, with a coefficient of variation of 46.9%. This criterion, which considers the impact of wind on restoration sites, was ranked variably by participants, but not as widely debated as proximity to main channels.

Proximity to existing Salt marshes had a lower mean (16.0) compared to other criteria, and it also exhibited the lowest coefficient of variation (38.8%). This lower variation implies that there was more consensus among stakeholders about its relative importance. Most respondents seemed to agree on the importance of maintaining proximity between restoration sites and existing salt marshes, likely reflecting a shared understanding of the ecological benefits of connected habitats.

Lost Salt marshes since 1840 showed a mean of 15.8, with a coefficient of variation of 42.8%. This indicates that stakeholders moderately agreed on the relevance of historical location for restoration decisions, though there was still some variability in how much weight this factor should have.

Seagrass Protection, with a mean of 15.7 and a coefficient of variation of 47.7%, reveals that stakeholders considered this ecological factor relatively important, though there was considerable variation in their responses.

Lastly, Water Quality, had the lowest mean (13.8) and a fairly low coefficient of variation (41%). This indicates that while it was ranked slightly lower in importance, there was a reasonable degree of agreement among stakeholders about its relevance.

In summary, the analysis shows that while some criteria, such as Distance from Canals and Seagrass Protection, generated more variability in stakeholder opinion, others, like Proximity to existing Salt marshes and Water Quality, saw more consensus. This variability likely reflects the diverse priorities and expertise of the different stakeholder

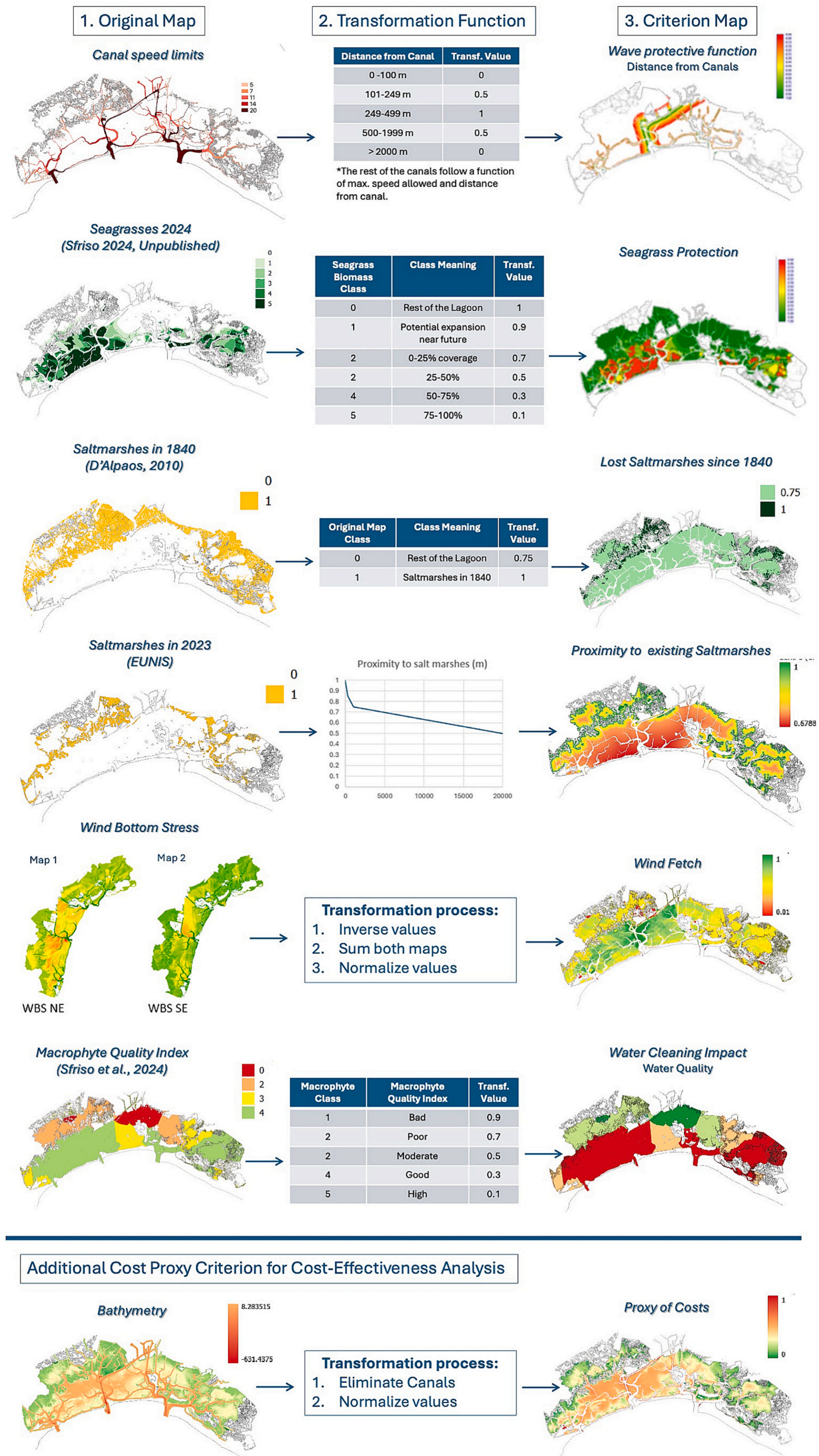

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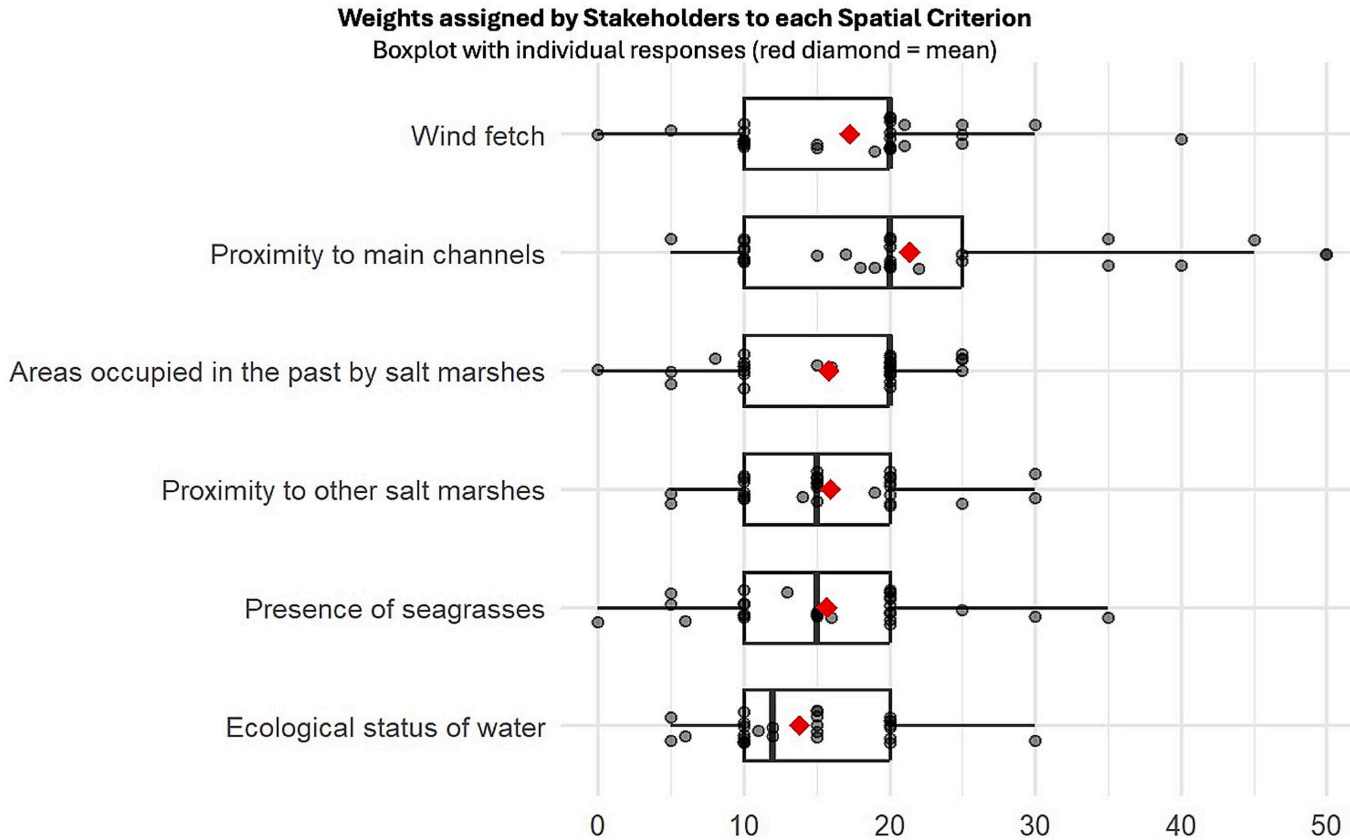
Fig. 4. Variable Transformation process of the 6 selected criteria, as well as the cost proxy at the bottom. The maps shown in the first column ("Original variable") correspond to the original input data. The second column describes the type of transformation applied to each variable. When the variable is discretized, the transformation is presented in a table format, where the first column reports the thresholds or original values and the second column shows the corresponding "Transformed values" (for example in the Seagrasses layer). In other cases, different transformation approaches are used. For example, a utility function may be applied (as in the Salt Marsh 2023 layer), or a descriptive approach is provided, explaining step by step the transformation performed (for example for the Wind Fetch layer). Finally, the last column presents the resulting output map, which is the standardized and normalized layer (from 0 to 1) used as input for the MDCA.



Summary statistics (Spatial criteria)

Mean, median, standard deviation, and coefficient of variation (CV)

	N	Mean	Median	SD	CV
Distance from Canals	29	21.41	20.00	12.44	0.581
Wind Fetch	29	17.28	20.00	8.10	0.469
Proximity to existing Saltmarshes	29	15.97	15.00	6.31	0.395
Lost Saltmarshes since 1840	29	15.83	20.00	6.89	0.435
Seagrass Protection	29	15.69	15.00	7.61	0.485
Water Quality	29	13.83	12.00	5.67	0.410

Fig. 5. Box plots presenting the distribution of weights (above) and table (below) showing the mean, standard deviation and coefficient of variation of each criterion.

groups, with some focused more on ecological factors and others on logistical or historical considerations. The coefficient of variation provides valuable insights into areas where there is agreement or debate, which can help guide further discussions in refining the criteria for salt marsh restoration.

The following box plots show the value distribution of responses (points), the interquartile range and the mean for each criterion.

In light of the considerable variability in stakeholder responses regarding the weighting of certain criteria, a sensitivity analysis was conducted to assess whether this variability translates into changes in spatial prioritization. By varying each factor weight by ±20%, the sensitivity indices were found to be relatively homogeneous across all criteria, ranging between 0.157 and 0.175 (see Supplementary Information SI.7). This limited variation indicates that no single criterion disproportionately influences the final suitability ranking and that the spatial prioritization remains robust to moderate changes in stakeholder preferences.

3.2. S-PMCA maps

This section presents the spatial results of the S-PMCA conducted to identify suitable areas for salt marsh restoration and rebuilding in the Venice Lagoon. To begin with, Fig. 6 shows the density of values of the results for salt marsh restoration and rebuilding in the Venice Lagoon under three alternative risk configurations: optimistic, balanced, and pessimistic (explained in detail in the next paragraph). These scenarios were generated using the Ordered Weighted Averaging (Csiszar, 2021) aggregation procedure within the MCDA framework. It is worth noting that we have masked out from the analysis all aquaculture concessions existing at the moment as well as the canals, since these areas are not allowed for restoration or rebuilding.

The histogram shown in Fig. 6 indicates that the three risk configurations follow a similar overall distribution pattern, confirming that the underlying spatial structure of suitability remains consistent across scenarios. However, the distributions shift along the suitability axis according to the adopted decision strategy. The pessimistic configuration is concentrated in lower suitability ranges, reflecting the greater influence assigned to limiting criteria. The balanced scenario occupies an intermediate position, while the optimistic configuration is shifted toward higher suitability values, with a larger proportion of pixels concentrated in the upper ranges.

In addition, the optimistic scenario shows a more pronounced clustering of values within a narrower high suitability interval, indicating that many areas are considered favourable when risk aversion is reduced. By contrast, the pessimistic distribution appears more spread across lower and medium suitability classes, suggesting a more differentiated and restrictive prioritization. In general, the histogram confirms that the ordered weighting mechanism primarily affects the magnitude and concentration of suitability scores rather than altering the fundamental spatial logic of the model.

The balanced configuration distributes values more evenly across ordered values and generates intermediate results between the two extremes. For this reason, the balanced scenario was selected as the final representation, as it reflects a compromise between the three attitudes toward risk under consideration.

Fig. 7 shows the final Suitability Index for salt marsh rebuilding in the Venice lagoon using the balanced approach. For a more straightforward display of the suitable areas we have masked out all areas with a suitability index value below 0.5; since suitability values were standardized between 0 and 1, values below 0.5 indicate areas where constraints dominate, in particular these areas fall within areas with a high biomass of seagrasses or where wind-fetch levels are very unfavourable. We did not mask out seagrass areas directly since we have used a criterion based on biomass presence of seagrass in percentage per pixel, also we have discarded areas that are out of consideration for future restoration projects, since they fall within aquaculture concessions or existing salt marshes.

From the balanced configuration we observe a high suitability concentrated around the canal of Malamocco-Marghera, there are many factors contributing to this high suitability: the protective wave function, the absence of seagrasses, the nearness to existing salt marshes, and the water quality (i.e. the potential cleaning function of the salt marshes

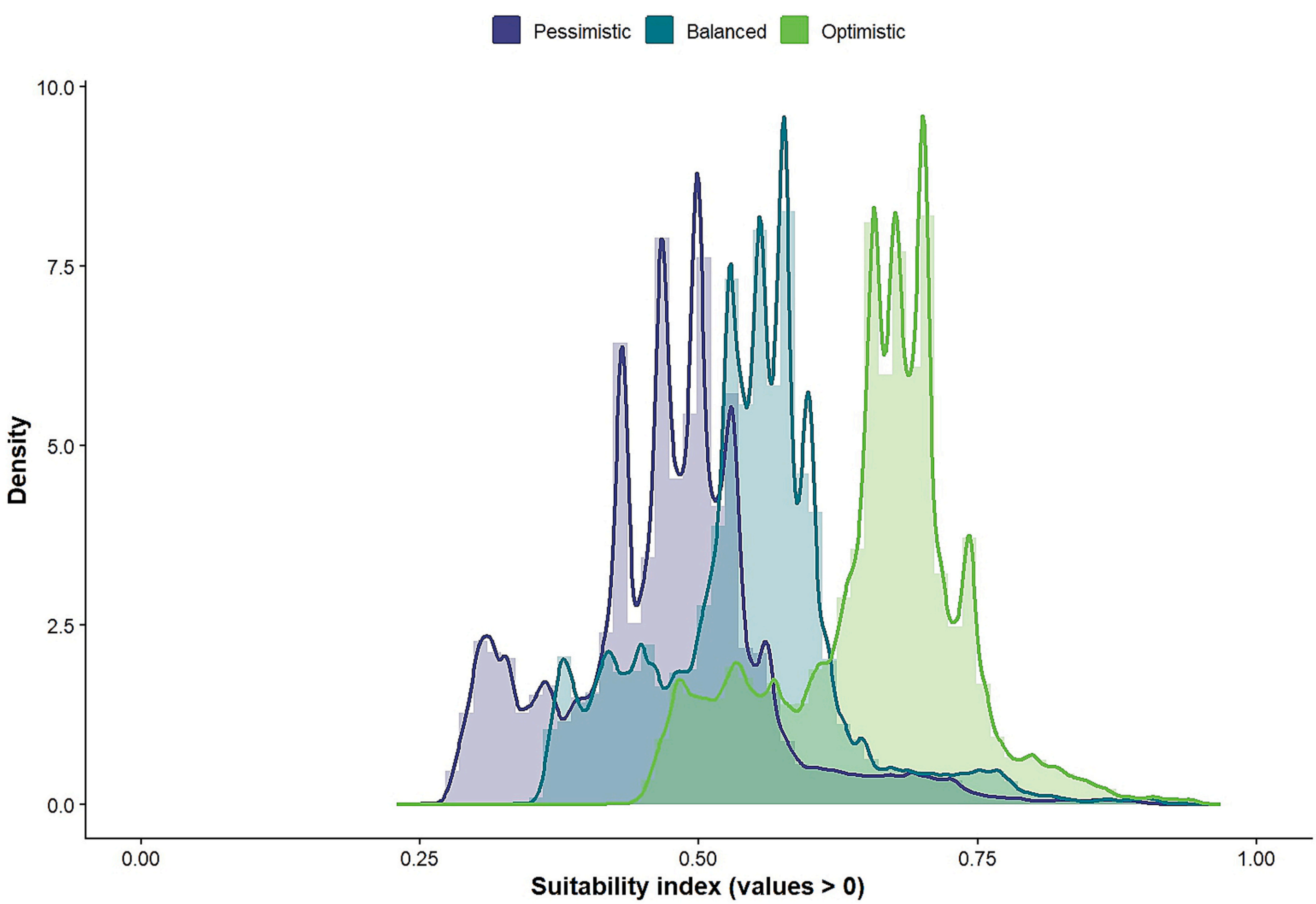


Fig. 6. Distribution of suitability index values under three risk attitudes: pessimistic, balanced, and optimistic.

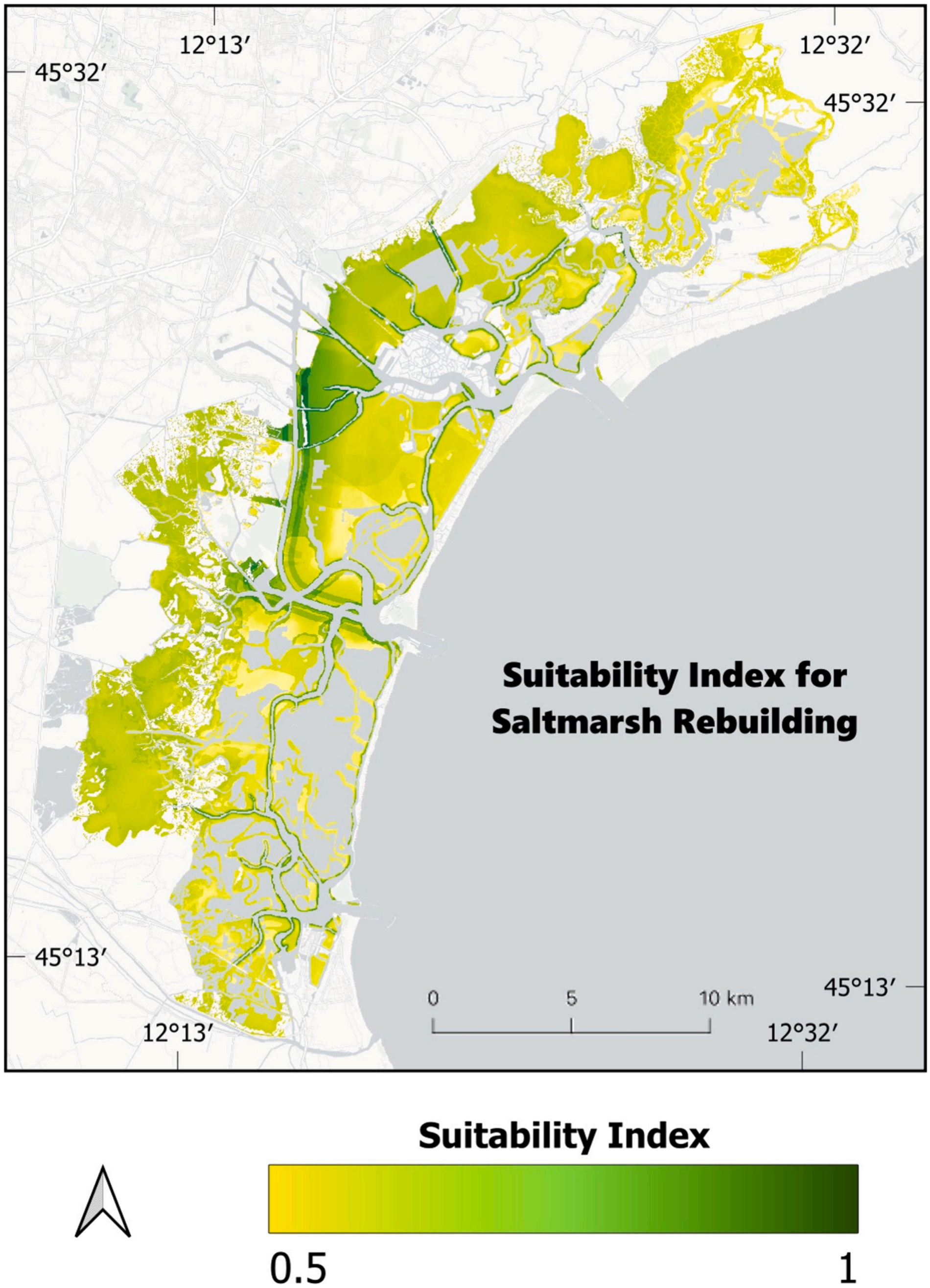


Fig. 7. Spatial Multi-Criteria Analysis of suitability for salt marsh rebuilding in the Venice Lagoon, we have masked out all values below a suitability of 0.5, as well as all subconcession areas and existing salt marshes.

in this area).

Fig. 8 displays the spatial distribution of the Cost-Effectiveness Index derived from the balanced suitability scenario, combined with a bathymetry-based cost proxy through a weighted aggregation, where costs are assigned negative values and suitability positive values, with suitability receiving approximately twice the weight of costs. The figure highlights only areas with suitability index values greater than 0.5 (from Fig. 7), thereby isolating medium to high ecologically suitable zones.

When considering all values, the index displays a heterogeneous pattern across the lagoon. Lower cost-effectiveness values, shown in red and orange, dominate large portions of the southern and central basins. These areas are generally characterized by deeper bathymetry and higher intervention costs, which reduce the overall cost-effectiveness despite the moderate suitability levels in some cases. In contrast, higher cost-effectiveness values, shown in green tones, are more spatially concentrated and typically located along lagoon margins and in shallower areas where sediment requirements for rebuilding are lower.

Areas with the best cost-effectiveness are mainly located at the periphery of the lagoon, close to the mainland, along protected shallow flats near existing marsh systems. These areas combine relatively high ecological suitability with lower expected sediment requirements, resulting in more efficient restoration potential. However, restoration success in coastal wetlands is strongly influenced by sediment availability, as adequate suspended sediment supply is necessary to sustain accretion processes and marsh stability (Liu et al., 2021). Areas characterized by low sediment inputs may therefore present greater restoration uncertainty and lower long-term resilience. Although sediment availability is recognized as an element of restoration success, this

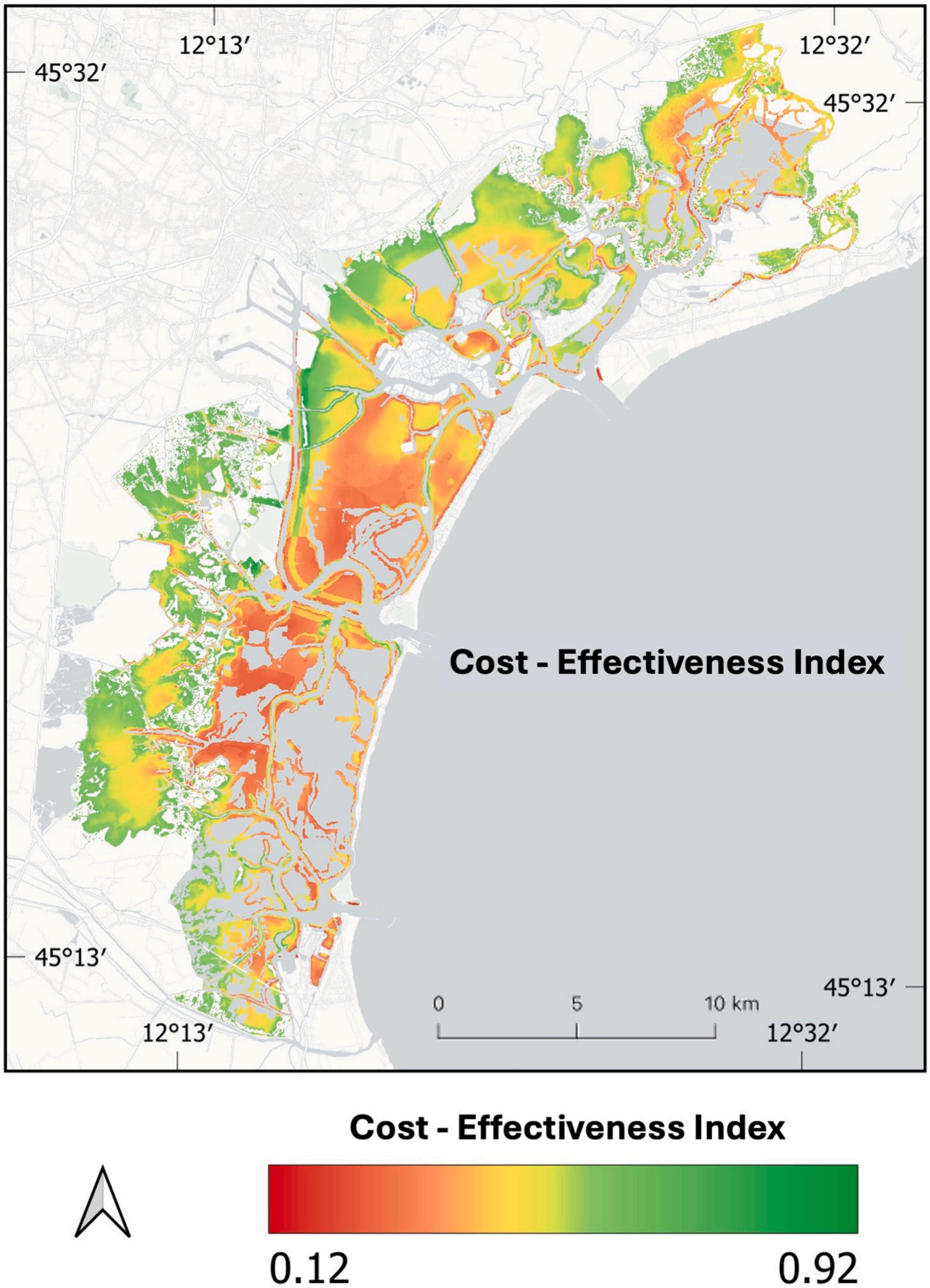


Fig. 8. Cost-effectiveness index map for salt marsh rebuilding. The map integrates multi-criteria suitability with a discounted cost proxy (50%), emphasizing areas that combine high ecological suitability with relatively low implementation costs, considering a constant salt marsh rebuilding technique. We have masked out all values below a suitability of 0.5, as well as all subconcession areas and existing salt marshes.

criterion was not incorporated into the spatial analysis due to the lack of spatially explicit data for the lagoon. This limitation is therefore acknowledged as an important area for future refinement of the analysis.

Finally, the map demonstrates that incorporating intervention costs alters spatial prioritization by filtering out deep and morphodynamically demanding zones. While many areas may be ecologically suitable, only a subset emerges as cost-effective under the assumption of constant restoration techniques. This highlights the importance of integrating economic feasibility into land use planning frameworks for large-scale wetland restoration (Nguyen et al., 2015).

Fig. 9 presents the clustering of the Cost-Effectiveness Index under the balanced scenario, grouping areas into four performance classes based on their combined suitability and estimated implementation cost. This classification represents one of the key outcomes of the analysis, as it translates continuous index values into operational restoration priorities.

Cluster 1 (High suitability and low-cost cluster) identifies areas with high suitability and low restoration costs. These zones are mainly located along peripheral lagoon margins and shallow areas where wind exposure is limited and sediment requirements are moderate. They offer the highest effectiveness to cost ratio and therefore represent the primary priority areas for rebuilding salt marshes.

Cluster 2 (High protection potential cluster) includes areas with strong lagoon protection potential, often located near important canals. While intervention costs are relatively higher, these zones provide significant wave mitigation benefits and limited ecological trade-offs, making them strategically important despite lower cost efficiency than Cluster 1.

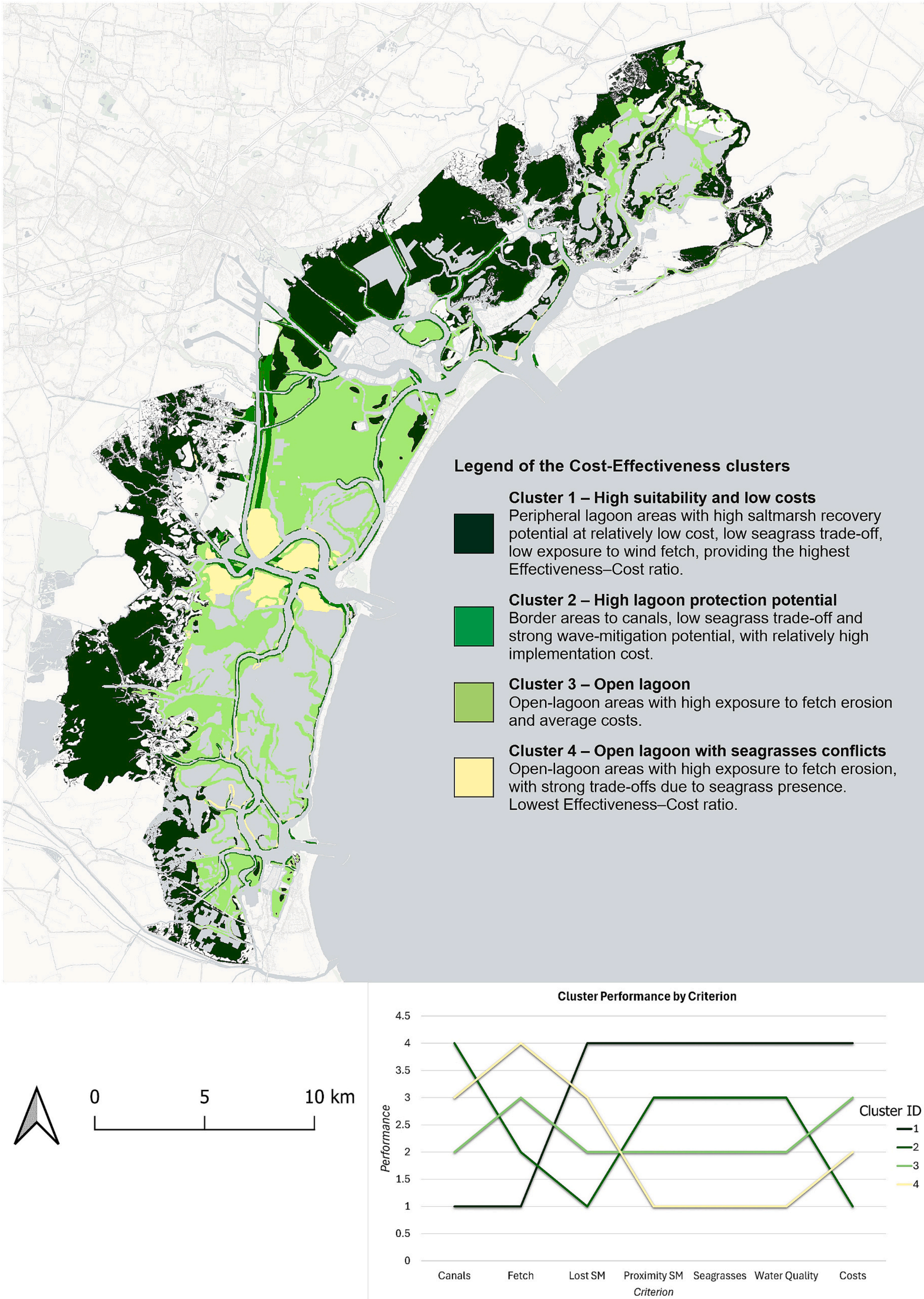


Fig. 9. Clusters with homogeneous combinations of Cost-Effectiveness based on all six criteria and a proxy of the costs based on the bathymetry.

Cluster 3 (Open lagoon cluster) represents open lagoon areas characterized by higher wind fetch exposure and average costs. These zones show moderate suitability but are more morphodynamically exposed, resulting in intermediate cost-effectiveness.

Cluster 4 (Open lagoon with seagrasses conflict cluster) identifies the least favourable areas. These are open lagoon zones with high exposure to wind fetch and strong trade-offs due to seagrass presence. Although restoration may be technically feasible, the combined ecological constraints and cost conditions result in the lowest effectiveness to cost ratio.

The spatial distribution clearly shows that the most cost-effective restoration opportunities are concentrated in protected shallow margins, while open and exposed basins are less efficient targets. The performance graph confirms this pattern, illustrating how Cluster 1 consistently achieves high scores in proximity to marshes, water quality, and low-cost conditions, while Cluster 4 is constrained by exposure and ecological trade-offs.

4. Discussion

The results of this study should be interpreted within the broader scientific debate on ecosystem services valuation and Nature-based Solutions planning. In this context and to our knowledge, no previous study has attempted a comprehensive mapping of the Venice Lagoon for prioritizing wetland restoration interventions. While MCDA has been used in Venice for navigation management, ecosystem health assessment, and coastal conflict analysis, its application to spatial prioritization of morphological salt marsh restoration represents a methodological novelty in this area of study. This is particularly relevant given the lagoon's decreasing salt marsh areas, sediment deficiency, exposure to relative sea level rise, combined with a complex multi-level governance structure and the many actors involved in a wide variety of activities (e.g. fishing, tourism, and transportation of people and merchandise, etc) within the lagoon of Venice, whose involvement and understanding of their expectations and needs is crucial for effective salt marsh restoration. We have identified three types of literature streams that are similar to this analysis by either using MCDA i) in the Venice lagoon, or ii) the mediterranean for ecological restoration, or iii) because of their use of S-PMCA for wetland restoration applied to other sites:

- The Venice Lagoon and MCDA: D'Alpaos and D'Alpaos (2021) proposed a prioritization of ecosystem services in the Venice lagoon through an Analytic Hierarchy Process; our study complements this perspective by focusing on one ecosystem - salt marshes - and operationalizing spatial prioritization through the involvement of stakeholders in the valuation process. Other studies in the Venice lagoon context have applied multi-criteria approaches to support decision-making, such as Pesce et al. (2018), who use Multi-Attribute Value Theory to compare alternative cruise ship route projects, and Casini et al. (2015), who develop a model-based decision support system combining biogeochemical modelling with multicriteria aggregation to evaluate trade-offs between environmental and economic objectives. While both approaches integrate environmental, economic, and social dimensions and adopt structured decision frameworks, they focus on comparing predefined management alternatives and are not spatially explicit. Building on this literature, the present study introduces a spatially explicit MCDA framework in which each pixel of the lagoon represents a potential alternative. This shifts the decision problem from selecting among alternative projects to identifying priority locations for salt marsh restoration and rebuilding.
- Ecological restoration in the mediterranean and S-PMCA: from a spatial modelling perspective, our approach is aligned with S-PMCA habitat suitability applications such as Bakirman and Gumusay (2020), who combined environmental variables and expert weighting to produce spatial suitability maps for seagrass ecosystems in the mediterranean. As in their study, expert elicitation and normalization of spatial criteria are central elements of the analysis. However, whereas Bakirman and Gumusay (2020) focus on habitat distribution modelling, the present study extends the logic toward restoration prioritization and explicitly incorporates a cost proxy, allowing the derivation of cost-effectiveness clusters rather than suitability classes alone.
- S-PMCA in wetland restoration: other studies have applied GIS-based multi-criteria analysis for wetland restoration prioritization, particularly through expert consultation. However, we did not identify studies incorporating a spatial cost-effectiveness analysis, likely because suitable cost proxies are often difficult to define and operationalize spatially. A second distinction concerns the way suitability areas are represented. Most of the studies reviewed here do not provide a continuous spatial suitability index (with the exception of Uribe et al., 2014), but instead identify restoration priorities in a discrete manner, for example by classifying areas into priority categories such as “Priority 1” or “Priority 2”, and in some cases only identifying the highest-priority areas. Finally, many of these studies have applied Simple Additive Weighting or their OWA approach does not show how risk aversion influences their results (e.g., Rahman et al., 2014; Kauffman-Axelrod and Steinberg, 2010; Uribe et al., 2014; Aguirre-Salado et al., 2017; Widis et al., 2015; Maleki et al., 2018).

Future improvements to the analysis presented in the following points could strengthen the framework in several directions:

- One interesting possibility is to include biodiversity as a criterion, by integrating the presence and relative abundance of bird species of community importance, in accordance with the Birds Directive (Directive 2009/147/EC). An additional criterion could be included in the S-PMCA.
  Indeed, the relevance of the lagoon salt marshes, both natural and man-made, in supporting birds is widely acknowledged, as they play a crucial role for numerous waterbird species which rely on these unique habitats for nesting, feeding and resting, not only during migration periods, being used as “stop over sites”, but in all phases of their biological cycle (Scarton and Valle, 2021). Notably, in recent years, an increasing use of artificial salt marshes by waterbirds for breeding purposes has been observed. This shift has been associated with the growing frequency and intensity of high-tide events and extreme weather conditions during the reproductive period (May–June), which can lead to partial or complete flooding of natural salt marshes, resulting in nest loss and chick mortality for several species. Artificial salt marshes are often characterized by higher elevations compared to natural ones (Tagliapietra et al., 2018; Bonometto, 2003), which may reduce the risk of flooding and provide more suitable conditions for breeding waterbirds under current and projected climate conditions (Scarton and Valle, 2024).
  However, it is important to underline that elevation is a critical parameter in salt marsh functioning, and excessively elevated systems may not reflect natural marsh dynamics. Such conditions can affect vegetation composition, potentially favoring invasive species, and may limit the provision of other ecosystem services. Therefore, while higher elevations may benefit specific species such as breeding waterbirds, they may also involve trade-offs with respect to ecological integrity and overall restoration success. These aspects should be explicitly considered when moving from prioritization to detailed design of implementation projects.
  In this context and considering the strategic importance of certain artificial salt marshes in supporting breeding populations of species of conservation interest, the inclusion of criteria related to the presence and abundance of nesting bird species could represent a further key element in the prioritization of restoration actions within

the lagoon. This is exemplified by an artificial salt marsh located approximately 200 m from the historic city centre of Venice, which hosts a breeding colony of more than 3000 pairs of Sandwich Terns (*Thalasseus sandvicensis*) (L. Panzarin, pers. comm.), representing the largest colony in Italy and one of the largest in the Mediterranean, and accounting for over 80% of the estimated national breeding population of the species (Scarton and Valle, 2024).

- Another relevant improvement to the present analysis concerns the incorporation of long-term vulnerability to climate change. Venice is exposed to accelerating relative sea-level rise driven by both global climatic trends and local subsidence (Zanchettin et al., 2021), meaning that areas currently identified as suitable for restoration may experience changes in their relative elevation and hydrogeomorphic conditions over time. In addition, climate change may increase hydrodynamic stress and influence the long-term success of restored salt marshes. The resilience of these ecosystems depends on their capacity to maintain elevation through sediment accretion, and previous studies have shown that sites with limited sediment availability are more vulnerable to wetland loss (Day et al., 1998; Fagherazzi et al., 2020). Furthermore, the future operation of the Mo.S.E flood protection system (Modulo Sperimentale Elettromeccanico, a system of mobile storm-surge barriers designed to protect Venice from high tides and extreme water-level events) may alter sediment exchange between the lagoon and the Adriatic Sea, potentially reducing sediment deposition on marsh surfaces and affecting marsh persistence (Tognin et al., 2021). Consequently, while the suitability maps presented here reflect current environmental conditions, future restoration planning would benefit from incorporating projections of sea-level rise, subsidence, sediment dynamics, and Mo.S.E operation scenarios to evaluate the long-term resilience and viability of restoration sites.
- Moreover, this study would have benefited from an analysis disaggregated by stakeholder type, which could have revealed areas of convergence and divergence in preferences across different groups. However, respondents were not required to provide personal or organizational affiliation information. This decision was made to protect privacy, encourage participation, and account for the relatively small sample size. While appropriate for maximizing response rates, the absence of stakeholder-type data limited our ability to examine heterogeneity in preferences, representing a potentially valuable avenue for future research.
- Finally, this study would benefit from a more detailed representation of restoration costs. In the present analysis, bathymetry was used as a spatial proxy for restoration costs, under the assumption that deeper areas require larger volumes of sediment and therefore entail higher restoration expenditures. Before adopting this approach, we compared the costs of three salt marsh restoration projects implemented in 2022 and found remarkably consistent costs per hectare, averaging approximately €30/m^3 (2022 prices), with variations of less than ±€1/m^3, another source is Pernice et al. (2024) who indicate that the price for the first phase (intervention to protect the edges) is €362/LM (linear meter) and second phase (nourishment of the saltmarshes) is €19/m^3 of sediment nourished. This provided some support for treating restoration costs as broadly comparable across sites and focusing on bathymetry (volume of sediment) as the primary spatial determinant of cost differences, however behind the similar costs we calculated in these three restoration sites, the techniques of restoration might have been similar and the distance to sediments also. Therefore, actual restoration costs may also be influenced by factors not captured in this analysis, including sediment availability, transport distances of sediment, sediment quality, logistical constraints, and restoration material. Due to the lack of spatially explicit datasets and the technical complexity associated with these variables, they were not incorporated into the present analysis. Future research could integrate these additional dimensions to refine estimates of spatial restoration cost-effectiveness.

5. Conclusions and policy implications

This study provides an operational framework for prioritizing salt marsh restoration in the Venice Lagoon by integrating stakeholder perspectives, spatial ecological criteria, and economic feasibility within an S-PMCA framework, with the following main findings:

- The elicitation of criteria importance revealed both consensus and divergence among institutional actors, making explicit the trade-offs between morphodynamic risk, ecological opportunity, and governance constraints. The use of the Ordered Weighted Averaging method allowed the systematic exploration of different risk attitudes while preserving stakeholder defined importance weights, demonstrating that the core spatial logic of restoration suitability remains robust across optimistic, balanced, and pessimistic strategies.
- Under the balanced configuration, priority areas consistently emerge along protected lagoon margins and near the Malamocco-Marghera canal, where the wave protection function, poor water quality, ecological connectivity, and acceptable cost conditions converge. When intervention costs derived from bathymetry are incorporated, priority areas do change, clearly demonstrating that ecological suitability alone is insufficient for effective planning. Only a limited subset of areas achieves high effectiveness-cost ratio, indicating where restoration investments would generate the greatest returns in terms of ecological function per unit of cost.
- In the context of climate adaptation, sediment imbalance, and increasing operational constraints linked to the Mo.S.E. system, restoration planning cannot rely solely on ecological criteria. It must integrate cost efficiency, risk management, and be inclusive by considering stakeholder perspectives and vision. The framework presented here offers a replicable decision support tool capable of guiding large scale coastal restoration under the European Green Deal, balancing ecological resilience with economic realism and governance feasibility.

These results have direct policy implications. First, they provide a defensible spatial basis for allocating limited public funds toward high impact restoration zones. Second, they support phased implementation strategies by distinguishing between immediately viable areas and those requiring higher investment or additional protective measures. Third, the participatory design enhances institutional legitimacy, reducing the risk of conflict in a governance system characterized by overlapping mandates and sectoral pressures.

CRediT authorship contribution statement

Perla Irasema Rivadeneyra García: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Caterina Dabalà:** Writing – review & editing, Data curation. **Francesca Coccon:** Writing – review & editing, Investigation. **Adriano Sfriso:** Data curation. **Silvia Torresan:** Writing – review & editing, Data curation. **Paolo Comandini:** Writing – review & editing, Methodology. **Salvatore Causio:** Writing – review & editing, Data curation. **Fabienne Horneman:** Writing – review & editing, Data curation. **Ivan Federico:** Data curation. **Carlo Giupponi:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 5.4 to correct language. The authors subsequently reviewed and edited all content and take full responsibility for the final manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2026.182039.

Data availability

Data will be made available on request.

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