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# Long-term adaptation pathways for Venice and its lagoon under sea-level rise

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**The substantial risks posed to Venice and its lagoon by ongoing and projected sea-level rise (SLR) require unprecedented long-term adaptation strategies. We map the evolution of development pathways and the progressive shrinking of the solution space as SLR advances, identifying adaptation tipping points and analysing the relative pros and cons of alternative measures. The analysis highlights trade-offs among environmental quality, heritage preservation, social well-being and relevant Sustainable Development Goals, and costs increasing with SLR. With present insufficient greenhouse gas mitigation policies, the current open lagoon strategy, with mobile barriers and multiple accommodation measures, is likely to encounter hard limits within the current century. Follow-up strategies include ring-dikes isolating the city from the rest of the lagoon, or a closed lagoon with permanent coastal dams, each preserving different combinations of values while entailing major ecological and socio-cultural transitions. Under extreme SLR, relocation of monuments to suitable inland areas and abandonment would be the only remaining strategy, which might become unavoidable in the 22nd century under current climate policies and an Antarctic ice-sheet collapse. Rapid mitigation could still avoid the most disruptive long-term outcomes.**

**Keywords** Venice, Sea-level rise, Climate change, Adaptation pathways, Sustainable development

Venice and its lagoon are an iconic environment, with outstanding and multiple cultural, monumental and environmental values, which in 1987 led to their inclusion among the UNESCO world heritage sites as “an inseparable whole”[1,2]. This lagoon, covering about 550km$^2$, is the largest in the Mediterranean. It hosts important biodiversity, aquaculture activities and provides substantial ecosystem services. These outstanding values, the huge flow of tourists (above 22M visitors per year[3] with a turnover worth about 2-3G€ per year), the presence of a major port, and population decline from 170,000 in the early 1950’s to less than 50,000 in 2024[4] make Venice a sustainability hotspot.

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The preservation of Venice has been a growing concern, as it has been increasingly flooded during the last 150 years, with 18 out of 28 extreme events (flooding of more than 60% of the city) in the last 23 years[5]. This is due to relative sea-level rise (SLR)[6], which has until now been caused in approximately equal parts by global SLR and local land subsidence due to natural processes and anthropogenic activities[7,8]. Since 2022, a system of mobile barriers (MoSE, Modulo Sperimentale Elettromeccanico[9,10]) has prevented extensive floods. MoSE closes the three lagoon inlets during storm surges and lies on the bottom under normal conditions, thus allowing navigation and water exchange with the open sea. The process leading to MoSE was triggered by the dramatic 1966 flood[11] and initiated in 1973, when the Italian government established a legal framework for safeguarding Venice. MoSE has demonstrated its capability to protect the city, but the increasing number of closures due to future SLR will jeopardize its viability and have serious impacts on the lagoon ecosystem[7,12–14].

SLR in the North Adriatic Sea is expected to closely follow the global SLR, posing unprecedented adaptation challenges, as in 2020 more than 50% of Venice lies 0.80-1.20 m above the mean sea level (MSL), with a tidal range of about 1 m. By 2100, compared to beginning of the century, the SLR in Venice is expected to reach 0.42m under a low (RCP2.6) and 0.81m (up to 1.80m cannot be excluded) under a very high (RCP8.5) emissions scenario[8]. This would lead to 15%, 70% and 98% of the city centre being flooded daily at the astronomical tide maxima without defence structures. In 2300, global SLR will be in the range 0.3-3.1m and 1.7-6.8m in a low and very high emissions scenario, respectively, while a 16m rise cannot be ruled out[15].

Since the establishment of Venice, centuries of multiple and diversified large scale human interventions have shaped an original natural lagoon in the current strongly anthropic environment (Fig.1), such as in the 15th and 16th centuries river diversions to prevent sediments from filling the lagoon[16] and since the late 19th century the construction of embankments to prevent the lagoon from expanding inland[17]. Consequently, the lagoon is surrounded by polders resulting from the large subsidence that affected these former wetlands[18]), which are kept dry by a large network of pumping stations and drainage canals (Fig.2). Ongoing and future SLR poses unprecedented risks to this unique environment. Given grossly insufficient international efforts to reduce greenhouse gas emissions[19] and the inertia of SLR, it is essential to contemplate radical transformations for the city of Venice and its lagoon, considering the preservation of its monuments, lagoon ecosystem, traditions and cultures, economic prosperity, well-being and safety of citizens, which in the absence of adaptation would ultimately be lost.

The objective of this study is to map the evolution of the adaptation solution space under rising sea levels and to identify how physical, ecological, social and economic constraints progressively limit the viability of alternative strategies. This study does not aim to perform a cost–benefit analysis, which is neither feasible nor appropriate given the irreplaceable nature of Venice's monumental and cultural heritage and the multidimensional values that cannot be (or would highly debatable) expressed in monetary terms. Indicative cost estimates are used comparatively, to illustrate feasibility thresholds rather than to determine optimal choices.

To provide the necessary counterfactual context, we qualitatively describe, for each strategy, the main values that would be preserved relative to a no-action baseline. This framing clarifies that the analysis considers not only what adaptation costs, but also what each pathway effectively saves, thereby situating the results within a decision-relevant perspective.

## Results

### Adaptation strategies: suitabilities, limits and costs

Based on the available knowledge and technologies, we consider four strategies to address the risks posed by SLR to Venice and its lagoon: open lagoon, ring-diking, closed lagoon and retreat, each of them combining multiple measures with different SLR adaptation capabilities and costs (Figs.3, 4). For each strategy, we also indicate which social, economic, environmental and cultural values would be preserved relative to a no-action baseline. This qualitative counterfactual provides the necessary context for interpreting the indicative cost thresholds and clarifies that the comparison concerns not only what each option costs, but also what it allows Venice to retain as sea level rises.

#### *Open Lagoon*

The open lagoon strategy involves the present system of mobile barriers (MoSE), which closes the lagoon inlets during high waters to reduce flood risk, while remaining otherwise open. Relative to a no-action baseline, the open-lagoon strategy initially preserves the lagoon ecosystem, the monumental and cultural heritage, economic activities and residents' well-being, though its effectiveness rapidly diminishes as future relative SLR sets a limit to MoSE's functional lifetime by increasing frequency and duration of closures[7]. As closure frequency increases, the probability of malfunction or delayed operation rises, reducing the level of protection afforded to monuments and the safety of residents[14]. addtitionally, this would limit port operations[13], degrade the lagoon ecosystems, and, in the case of multi-day long closures, require an appropriate sewage treatment system for water quality and a large-scale pumping system to maintain lagoon levels below sea level. Altogether, an increased frequency and length of closures will result in higher failure risk and additional costs (see section Methods for all cost estimates), which are in the range of 0.25-1.1G€ for the large-scale pump system, 0.3G€ for the sewage treatment system, between 1.5 and 3.5G€ assuming a 0.75 m SLR (with respect to the beginning of the 21$^{st}$century, here and the rest of the text) until 2100 for MoSE operations and disrupted port activities during closures, growing to more than 0.1G€ per year in case of relative SLR above 1m. Alternatively, the relocation of the port could be considered (with costs of about 4.1-4.5G€). Adopting 2 or 6 months as an upper limit for annual closure duration would imply a relative SLR of about 0.50 or 0.75 m as the suitability threshold for this strategy[7].

Complementary accommodation measures can increase the effectiveness and extend the functional lifetime of the open lagoon strategy.

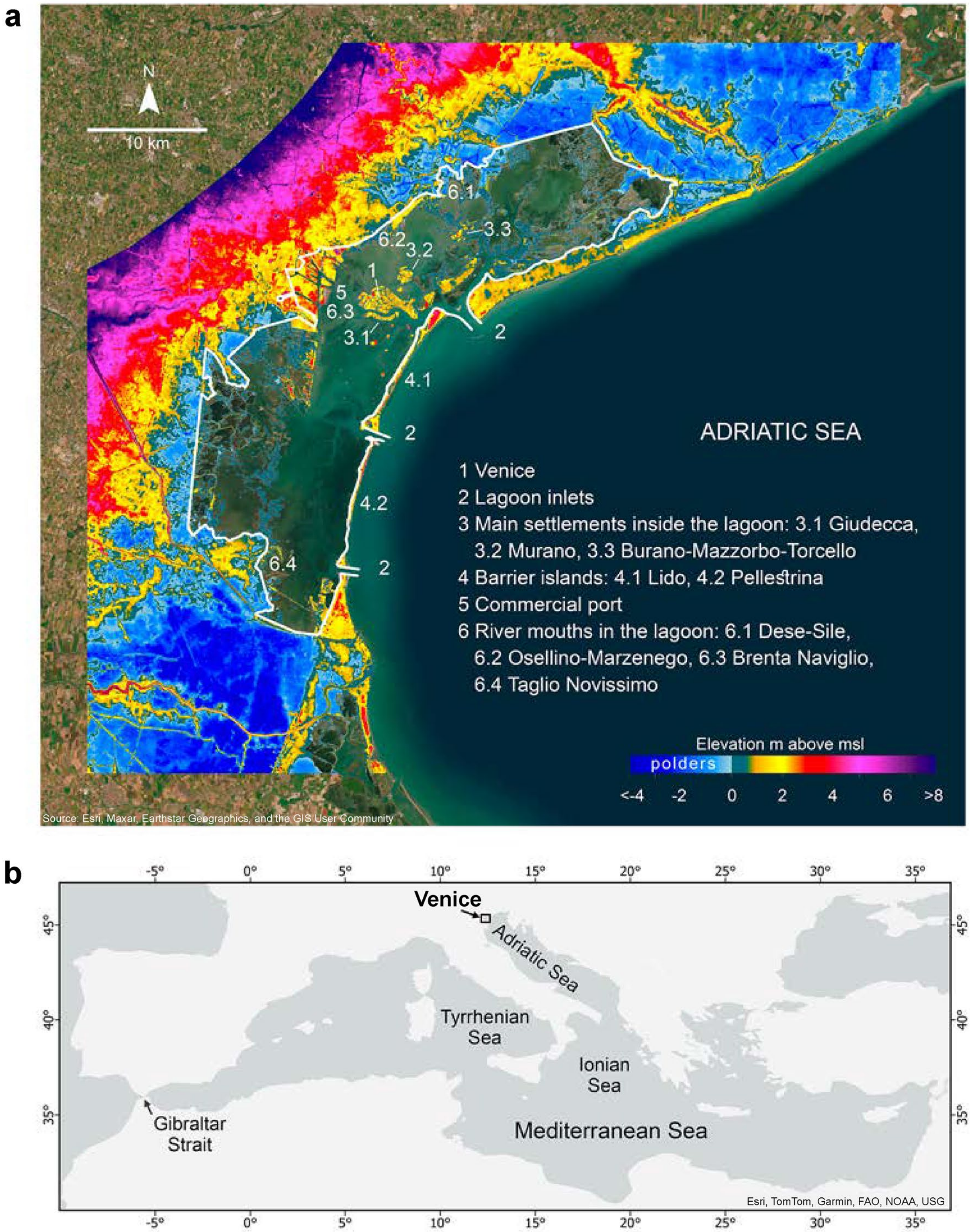


**Fig. 1**. **a**) Color bar shows the elevation of land areas around the Venice lagoon and of the lagoon islands superimposed to the background satellite picture. Values are with respect to the MSL at the end of the 20th century. The white line represents the jurisdictional boundary of the lagoon, which approximates its physical boundary except at the port. **b**) the Venice lagoon in the Mediterranean region. Maps produced using ArcGIS Pro 3.6.0 (Esri; https://www.esri.com/) with the Esri World Imagery basemap (credits: Esri, Maxar, Earthstar Geographics, and the GIS User Community).

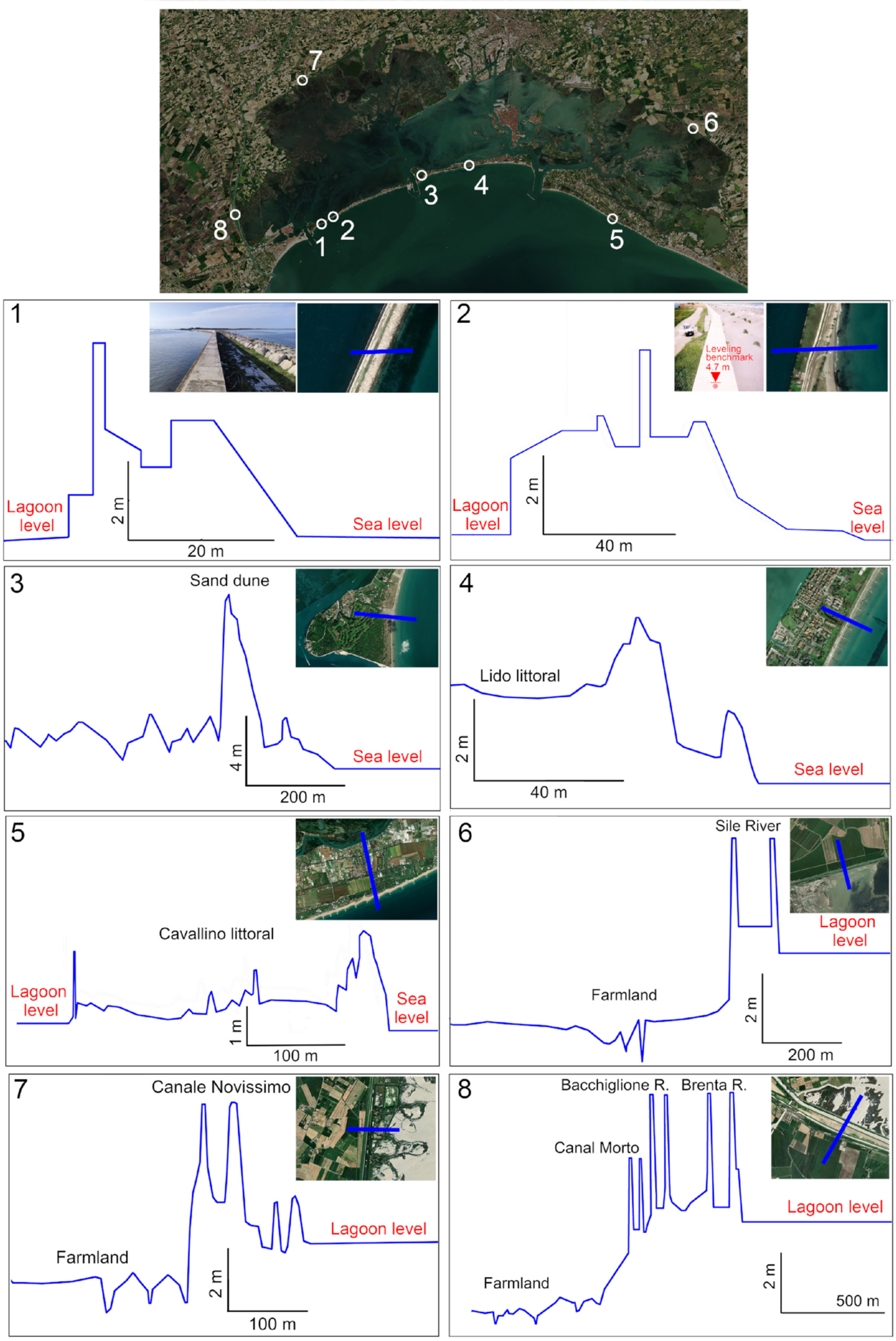


**Fig. 2**. Elevation profiles of the Venice lagoon boundaries outlining the elevation of primary defenses with respect to the present lagoon and sea level: dike (1) and seawall (2) on Pellestrina barrier island; dunes (3) and embankment (4) on Lido barrier island; dunes and embankments along the northern littoral (5); and embankments protecting the polders along the lagoon border (6, 7, 8). The locations of the transects are displayed on the map at the top of this panel. The panels report also the name of rivers and canals that are crossed by the transects. Data were downloaded from the MASE geoportal (https://gn.mase.gov.it/portale/en/home). Transect locations are shown on the overview map (top) and by the blue lines in the inset images; each panel also lists the names of the rivers and canals crossed by the transects. The overview map is based on a Sentinel-2 image (acquired 12 April 2024) accessed via Copernicus Browser (https://browser.dataspace.copernicus.eu/) on 8 January 2026 and processed by the European Space Agency (ESA). Insets use the Esri World Imagery basemap (credits: Esri, Maxar, Earthstar Geographics, and the GIS User Community). The figure was produced using ArcGIS Pro 3.6.0 (Esri; https://www.esri.com/) and Office 365 software (Microsoft; https://www.microsoft.com/).

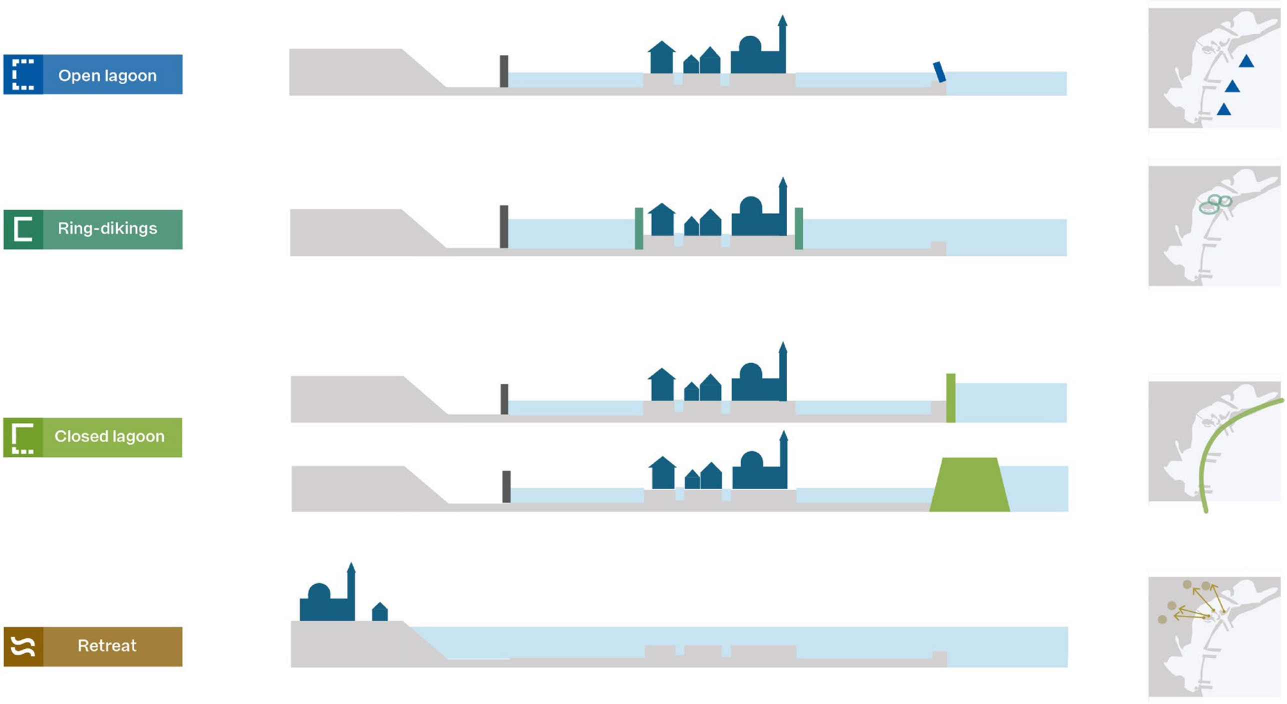


**Fig. 3**. **a**) Illustrations of the strategies described in this article, with an additional line showing superlevees (part of the closed lagoon strategy).

Measures for large-scale accommodation include injecting seawater into the saline aquifers in the depth range 600 to 1000 m beneath the lagoon, to gradually raise its central portion by up to 0.30 m over a 10-year period, with even a 0.50 m uplift possible if depths below 1000 m are considered[20–22]. Total costs of this measure are estimated in the range 0.3-0.4G€ and it could extend the effectiveness of the open lagoon strategy to a SLR of 1.25 m.

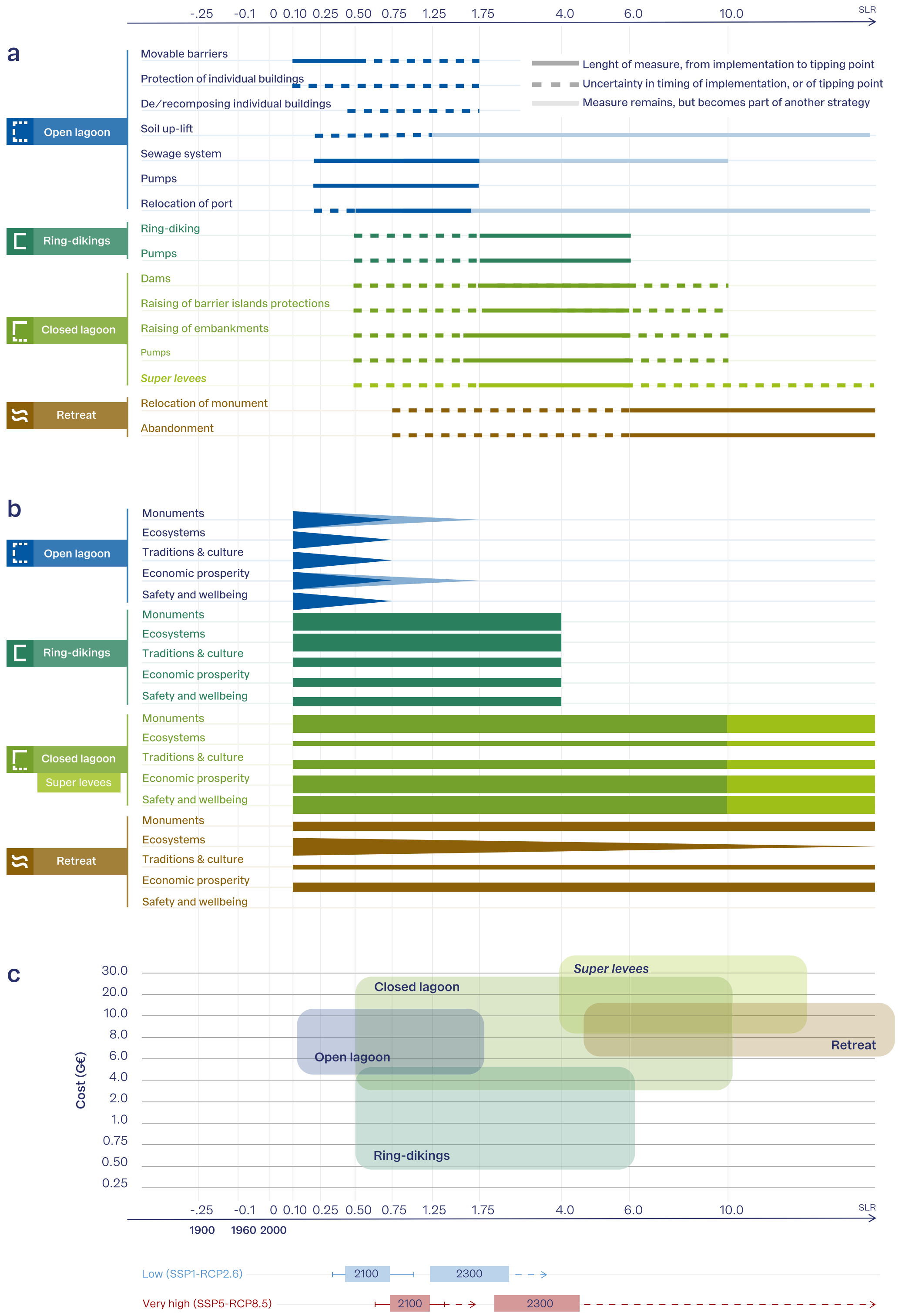
Since the 1960s, accommodation has been extensively implemented in Venice by raising street pavements, adapting the ground floor of individual buildings and placing removable door gates. This latter measure can be scaled up across the city by installing structures protecting monumental areas (with costs higher than 1G€), such as that implemented for the St. Mark's Basilica, but space availability and negative visual impacts limit it. De-composing and re-constructing in-situ individual buildings on new higher foundations would have costs from 2 to 6 G€ depending on the fraction of the city centre and height raised. These measures could extend the effectiveness of the open lagoon strategy to protect the main monuments, but not the rest of the city, for a SLR of about 1.75 m. These accommodation measures do not, however, safeguard lagoon ecosystems, traditions and cultural practices tied to lagoon use, safety and well-being of residents.

### *Ring dikings*

Ring-dikes consist of dikes isolating the city centre and other settlements from the rest of the lagoon, which remains connected to the open sea. Compared to no action, ring-diking preserves monuments, residential areas and most economic functions, while altering the traditional landscape and weakening the physical and cultural connection between the city and its lagoon. Ring-diking does not require the operation of the MoSE barriers and the lagoon remains continuously open to marine exchange. Consequently, lagoon ecosystems would evolve under sea-level rise, climate change and other anthropogenic pressures, but without the impacts of the engineering interventions of the open- or closedlagoon strategies. Ring-diking has to be complemented with an efficient city sewage system and systems of pumps maintaining the internal water level below the surrounding lagoon, with additional costs up to 0.65G€. Construction costs are estimated from 0.5 to 4.5G€ depending on the dike length and height[23]. Cost estimates are shown for ring dikes designed to withstand 2 m and 6 m of SLR, reflecting the fact that this strategy can technically be upgraded to protection levels in this range, depending on available space and structure heights. Impacts of ring-diking would be non-negligible on tourism, because of substantial landscape changes, but minimal on the ecosystems of most of the lagoon. Emergency preparedness would be required in the case of failure of the defence system. Propensity to live in Venice could be affected by lacking attitude to risk and loss of connection to the lagoon. Public and commercial transportation, the port location and its organisation would need to be completely redesigned.

### *Closed lagoon*

The closed lagoon strategy consists of transforming the lagoon into a coastal lake (similar to Marina Bay, Singapore and the IJssel Lake, The Netherlands). This strategy preserves the city's monumental fabric, residential



areas, and tourism activities, but sacrifices the natural lagoon ecosystem, thereby maintaining the urban cultural heritage while losing the environmental context that historically shaped it. At difference with ring-diking it would not affect the city landscape and safety issues will be similar to that of polders. It would require permanent dams across the lagoon inlets, raising of the barrier islands and of the landward embankments separating the lagoon from the surrounding polders, with costs that could be as high as 0.54G€, 4.8G€ and 20G€, respectively[23]. The technical limit of this strategy is determined by the maximum potential heights of dams and barriers and it would probably occur later than in the ring-diking strategy because the defence structures will be located far from the city without directly impacting it. The cost ranges corresponding to protection levels of 2 m and 10 m of SLR are reported, indicating that this strategy can in principle be extended to very high SLR values. Ecosystem and biota losses would be unavoidable. Actions would be needed to control water quality in the lagoon. The required system of permanently active pumps would be much larger than for the ring-diking strategy. The closed

◀**Fig. 4**. **a**) Measures involved in the four adaptation strategies and the SLR range for their functional lifetime (solid lines), with associated uncertainties (dashed lines) and continuation as components of other strategies (light solid line). Uncertainties are caused by decision processes, technical limits, dependencies on complementary measures. **b**) Suitability level of the four strategies for safeguarding monuments, lagoon ecosystem, traditions and cultures, economic prosperity, safety and well-being of residents. The thickness of the horizontal bars conveys qualitatively three relative levels (full, partial, nil) of suitability. For the open-lagoon strategy, bar thickness decreases with increasing SLR to represent its progressively diminishing effectiveness, while the light blue bars indicate the potential of accommodation measures. In case of retreat, absence of residents prevents the analysis of suitability for safety and well-being, while suitability for safeguarding ecosystems decreases with progressing SLR. c) Broad range of indicative costs (y-axis) versus SLR (x-axis) combining lifetime information from panel with cost data from sections "Land uplift by seawater injection ..." and "Indicative cost estimates..". The limits of the boxes are obtained considering the minimum and maximum values of measures in panels **a**) and **b**), capturing both costs and lifetime uncertainties. The bottom annotation indicates the approximate relative SLR values (with respect to the end of the 20th century, blue arrow) and SLR likely (boxes) and very likely (whiskers) ranges under low (green) and very high (red) emission scenarios for 2100 and 2300. Dashed arrows refer to the case of a large Antarctic contribution to SLR. Lead times are not considered. they might be multidecadal as in the case of MoSE and other flood barriers[28].

lagoon strategy could be scaled up to protect against even higher SLR by using a super levee approach, a structure with a width about 30 times its height, such as proposed for some low-lying areas of Tokyo[24,25] with costs likely exceeding 30G€. The closed lagoon strategy would force port relocation or provision of large-scale locks that would likely strongly affect its operation and profitability. Touristic activities and the residential environment would be affected only partially. A complementary function of both the ring-dike and closed-lagoon strategies is the possibility of managing pluvial and river inputs through dedicated pumping systems, which allow excess water to be discharged outside of the protected areas (see section Pluvial and river flood risks).

*Retreat*

Planned relocation and abandonment by residents are two components of the retreat strategy. Compared to a no-action counterfactual, this strategy preserves only selected monuments (if relocated), while the historical urban fabric, lagoon-based culture, traditional lifestyles, and most economic activities would be irreversibly lost. Without active management, substantial SLR would transform the present lagoon into a deeper marine environment, where non-indigenous species, warming and more saline waters would establish a new ecological regime, fundamentally different from the historical lagoon that shaped Venice's cultural and natural heritage. Planned relocation consists in dismounting buildings and reassembling them in new higher locations. This unprecedented and complex operation (applied at a small scale, e.g. for the Abu Simbel temple in Egypt[26]) would not prevent the loss of the cultural, historical and monumental assets of the original settlement. Upscaling former projects produces costs estimates in the range 1-10G€, but this could be increased ten times in the Venice context. The relocated monuments could be visited by tourists and new residential areas built around them. The flooded remains would progressively deteriorate and could be visited for a limited period by boat (and submarine). It would imply the loss of private properties with eventual compensation costs of order from 5 to 6.5G€[27]. Abandonment by residents could happen either gradually, as residents and activities move away as the flooded areas increase in time, or abruptly, after catastrophic events caused by the failure of the implemented defence system.

## Adaptation pathways

Adaptation pathways[29] result from combinations of the strategies over time, with adaptation tipping points (ATP) marking the switch from one strategy to another, when risk becomes too large (fig.5).

Nowadays, the system is in an incremental adaptation phase, during which the implemented mobile barriers defence system (MoSE) in combination with accommodation can efficiently maintain an open lagoon. Our estimate is that, when the relative SLR will be in the range 0.75-1.75m, an adaptation tipping point (ATP, where a strategy can no longer meet its intended goals) to a transformational phase will necessarily occur, and Venice and its lagoon will necessarily shift to a condition unprecedented in their long history with fundamental implications for the economy, ecosystems, residents and the universal value of the UNESCO property. This transformation is unlikely earlier than the 2070's, even in a very high emissions scenario, and remains unlikely until the 22nd century in a low emissions scenario. However, the increased risk of pluvial and river flooding during extreme sea-level events may reduce the operational lifetime of the open-lagoon strategy compared to the limits imposed by SLR alone. The SLR upper limit of the open lagoon strategy, corresponding to the successful implementation of all accommodation measures, depends on whether the socio-economic scenario will support them and on not fully explored technologies (e.g. uplifting the ground with pumping). The ATP could be anticipated if the MoSE would show signs of stress or malfunctioning or in the case of major failure leading to a catastrophic event during a high storm surge, which could even trigger the abandonment of the lagoon. Extending the open lagoon strategy to its upper limit by implementing accommodation options appears more expensive than the ring-diking or closed lagoon strategies.

When the ring-diking or the closed lagoon strategy would be adopted the system would enter into transformational adaptation, whose first part is a resilient development opportunity phase, where the present city structure and functioning are maintained, though the connection to the lagoon (ring-diking) or to the open sea (closed lagoon) would be disrupted. As the upper limit of the ring-diking is lower than that of the closed lagoon

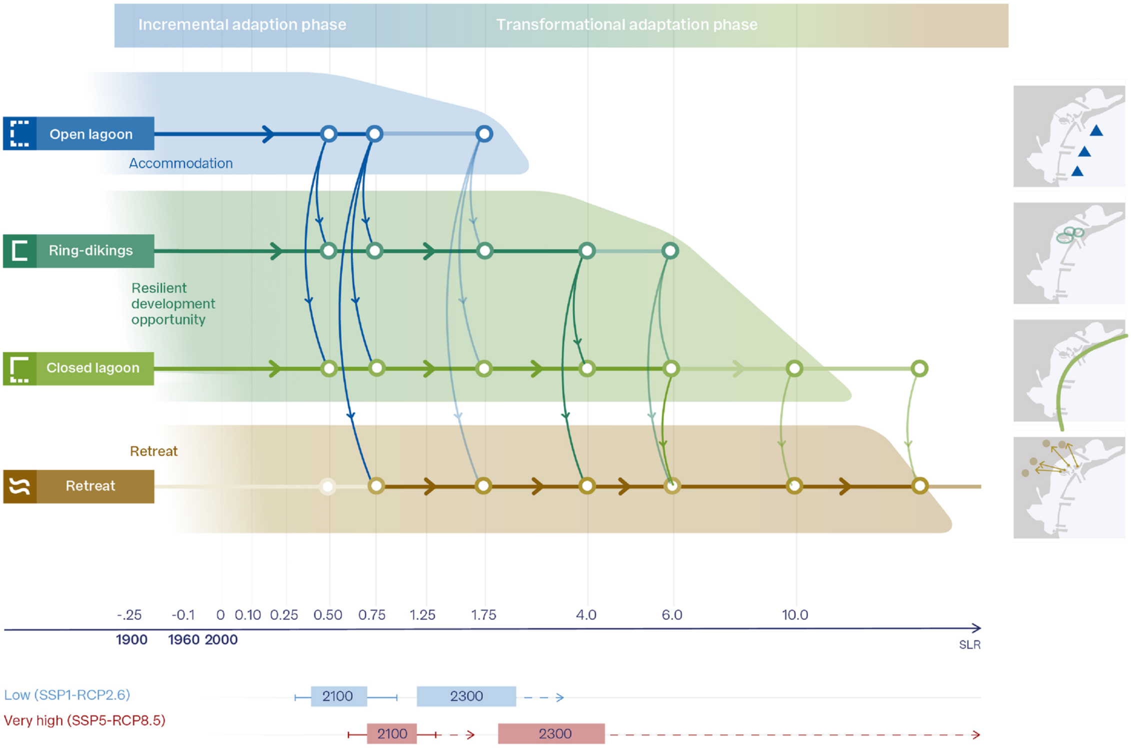


**Fig. 5**. Adaptation pathways and tipping points marking the switch from one strategy to another. This figure highlights the decreasing and shifting solution space with SLR as the system evolves from incremental to transformational adaptation, consisting in climate resilient development or retreat. Annotation at the bottom indicates the approximate relative SLR values (with respect to the end of the 20th century, blue arrow) and SLR likely range (boxes) and very likely (whiskers) in a low (green) and very high (red) emission scenario in 2100 and 2300. The dashed arrows refer to the case of a large Antarctic contribution to SLR.

strategy, the former could be adopted first and the latter postponed to a higher SLR. Transitioning towards the transformational adaptation phase before reaching the upper limit of the open lagoon strategy would be cheaper overall and it could be maintained up to a 6 to 10-meter SLR.

Retreat may be a plausible path before reaching the technical limits of other strategies, if the economic profits and socio-cultural reasons supporting the maintenance of the city structure critically diminish. Otherwise, the first ATP towards the retreat strategy is in the 4-10m SLR range. It would be determined by the capability of the dams to sustain the sea-level difference (depending on technology and geomorphology) and by the social acceptance of living in an area where a dam failure might not allow sufficient time to escape/evacuate. The decision to abandon by the population and the relocation of Venice would have costs higher than any former strategy except the construction of a super levee. In this strategy, the costs of raising the embankments separating the lagoon from the polders around Venice is not considered, as it needs to be analyzed in the context of the adaptation strategy of the wider North Adriatic coast to SLR, which is beyond the scope of this study. Retreat before the end of the 24th century is likely in a very high emissions scenario, but it is unlikely in a low emission scenario[30,31].

## Discussion

This discussion is structured around five key themes. First, we outline the multiple goals at stake and the limits of monetary valuation for cultural heritage. Second, we examine how strategy-dependent risks emerge from interactions with tourism, port activities and ecological drivers. Third, we discuss how rising sea levels introduce adaptation tipping points that progressively narrow the solution space. We then consider the long lead times required for major interventions, which make timely decisions essential. Finally, we situate the Venice case within the broader context of global coastal challenges.

Multiple goals must be considered when evaluating SLR adaptation strategies for Venice (Fig.6): preservation of monuments, lagoon ecosystems, living traditions and culture (goals linked to its UNESCO world heritage status and Sustainable Development Goals (SDGs) 11, 14, 15), and safeguarding economic prosperity, safety and well-being of residents (linked to SDGs 3, 8 and 9).

The four proposed strategies differ in the values that they can safeguard as SLR progresses. The open-lagoon strategy preserves all major values in the near term, but its capacity declines as closure frequency increases. Adding accommodation measures extends the protection of monuments and urban functions, but does not prevent the progressive ecological degradation associated with more frequent MoSE operations. Ring-diking

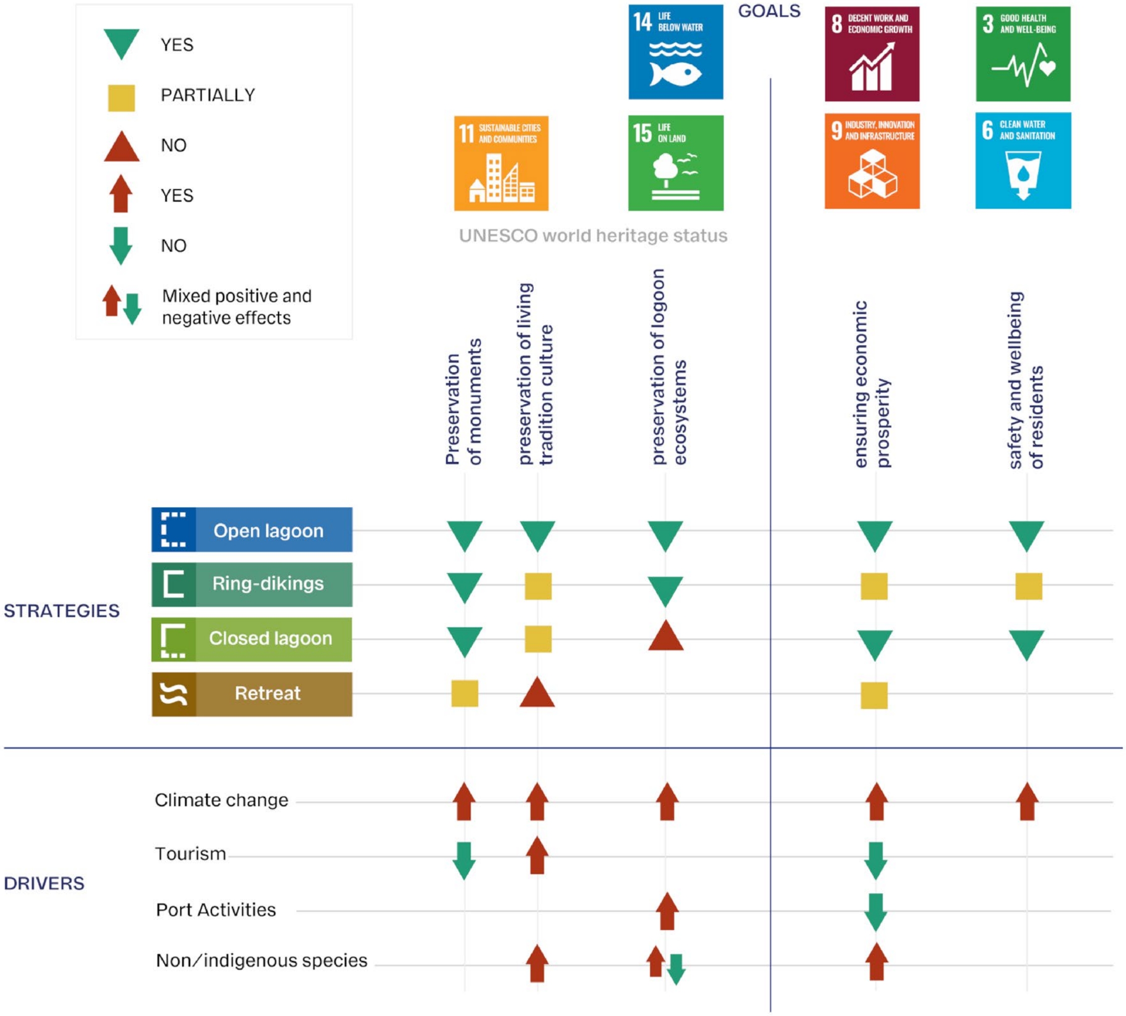


**Fig. 6**. Goals, adaptation strategies and drivers. Symbols show whether strategies achieve (YES/NO/Partially) each goal and drivers increase (YES/NO/Mixed) the risk of missing them. Open-lagoon effectiveness declines with SLR.

preserves monuments, residential areas and most economic activities for substantially higher SLR, while leaving the lagoon ecosystem largely free to evolve, but at the cost of weakening the cultural and physical connection between the city and its lagoon and introducing residual safety risks linked to dike failure. The closed-lagoon strategy maximizes protection of the monumental fabric and urban life at the expense of the lagoon ecosystem, which would be irreversibly transformed. Finally, retreat safeguards only selected monuments, with irreversible loss of the urban fabric, lagoon-based culture and present-day economic functions. Ultimately, the choice among adaptation strategies depends on the priority assigned to different values and on the resources available, notwithstanding that losses will be unavoidable under high SLR.

Protecting Venice's economic system (its real estate, infrastructure, port activity and tourism) would provide an economic rationale for even the most costly strategies, as the potential losses of a no-action future substantially exceed their indicative costs. In contrast, preserving the lagoon ecosystem, while environmentally beneficial, contributes only marginally to economic comparison. Citizens' well-being has measurable economic value, but it remains lower than the cost of a full-scale defence once SLR exceeds roughly 2 meters.

Methods for monetary valuation of non-market goods, including cultural heritage, can be applied, but they capture only a single component of value[32]. Monetary valuation can inform decisions when the expected changes in assets are marginal. But the potential loss of Venice is, by no measure, a marginal loss. While society must still assign a finite, though possibly very large "willingness-to-pay" to protect heritage, cultural values transcend monetary representation, making the integration of cultural and economic assessments indispensable for policy decisions. A unique historical asset such as the city of Venice is ultimately priceless: no monetary estimate can replace the cultural meaning and collective memory embedded in the city. This universal and irreplaceable value provides the fundamental motivation for maintaining protection for as long as technically feasible.

Risks depend on the adopted strategy and its interactions with other environmental drivers including tourism, port activities, and non-indigenous species. These drivers can amplify the impacts of SLR, making strategy-dependent risks a central element of long-term planning.

Frequent closures of the mobile barriers would affect water temperature and salinity[33], potentially reverse the ongoing decrease of pollution and eutrophication[34–36] and impact the lagoon morphology by decreasing the import of marine sediments[37,38]. Ecosystem risks would increase enormously under the closed lagoon strategy. Further risks are caused by ongoing and future warming[33,39,40], combined with mixed positive-negative effects of non-indigenous species on ecosystem services[40–42].

Living tradition and culture are threatened by accommodation measures that disrupt the city's internal connectivity and by strategies that alter the link between Venice and its lagoon, which would be completely lost under retreat. Further risks are posed by non-indigenous species increasingly impacting artisanal fisheries[43,44].

The safety of residents and visitors depends critically on the reliability of the current mobile barriers and of other defense systems and it will be threatened by insufficient funding, maintenance gaps or technical malfunctions. The health of residents would be at risk if measures to guarantee good water quality in and around the city are not thoroughly implemented.

All long-term protection strategies also carry the possibility of major structural failures. This aspect is particularly critical for the ring-diking strategy because of the immediate proximity between the dikes and the historic city. A failure of even a single segment during high sea levels would result in rapid inundation of the city centre, potentially with several metres of water depth and very limited time for emergency response. Although such failure modes lie beyond the scope of the present analysis, their existence underscores the need to complement long-term planning with robust risk-management and emergency-preparedness considerations.

Tourism and port activities are major contributors to local economic prosperity. While tourism helps sustain the city's current service infrastructure and contributes indirectly to the preservation of its monumental heritage, it can also reduce residents' quality of life, affect local traditions and culture[45] and increase pollution[46]. Tourism is broadly compatible with the open lagoon, closed lagoon, ring-diking strategies, which would maintain the existing visitor services. However, accommodation measures could affect tourism if the usable urban areas or the internal connectivity of the city decrease. Retreat strategies would imply a complete reorganisation of tourism and presumably major reduction of flows.

The future of the port of Venice will be strongly impacted by changing global commercial patterns (with eventually less coal and oil, more multimodal container shipping, and a decrease of large cruise ships) associated with climate change mitigation policies[47–50] and competition with other large ports in the North Adriatic[13]. Local adaptive actions include changes in port operation or quite possibly relocation of the port outside the lagoon.

Under a high-emission scenario and assuming no additional accommodation measures, the present open-lagoon strategy is likely to become inadequate before the end of the century as the frequency and duration of closures continue to increase. Because large-scale interventions, such as permanent barriers, ring dikes or major structural reinforcements, require lead times of 30–50 years, the effective window for initiating a transition to alternative strategies is already approaching. If procedures and institutional processes similar to those that led to the MoSE are followed, timely planning will be essential to ensure that any new strategy becomes operational before the current one reaches its functional limits.

Pathways include ATPs, which are associated with large societal and environmental consequences, the commitment of huge budgets (whose source/availability is not obvious) and long (multidecadal) preparation and implementation timescales. Decisions around ATPs are shaped by society's capacity to absorb the required changes, including institutional readiness, long-term financial commitments and the acceptability of trade-offs among competing goals. In extreme cases abandonment might result from limited budget, declining cultural identity, shrinking population and catastrophic events.

High SLR would threaten permanent flooding of large densely populated and highly productive areas along the entire North Adriatic coast (with 4,800 km$^2$ of land below 2 m elevation) and all adaptation strategies for Venice and its lagoon need to be embedded within a large-scale regional adaptation strategy rather than considered in isolation.

The adaptation solution space will progressively shrink with SLR as in many low-lying regions[51]. For Venice this contraction implies a transition from the present open lagoon strategy (incremental adaptation) to the ring-diking or closed lagoon (the opportunity window for resilient, transformational adaptation) and ultimately to relocation-abandonment during the irreversible retreat phase under very high SLR. The timing of these transitions will depend on the rate of SLR. Abandonment of the open lagoon strategy appears unavoidable on multi-centennial time scales. While it could be postponed to the 22nd century under a low emission scenario, it might be required within the end of the 21st century under a very high emission scenario. Mapping the progressive contraction of the solution space therefore informs decision-makers not about which option is optimal in economic terms, but about which values can still be preserved and for how long as sea level continues to rise.

Venice exemplifies the challenges that many low-lying coastal areas will face due to SLR over the coming centuries[52], as illustrated by the Maldives[53], the Netherlands[54–56], and coastal cities[57]. Most populated low-lying areas are already engaging in adaptation to manage inundation and flooding , yet current approaches will probably be able to work for limited time as sea level continues to rise. Ultimately difficult and costly decisions are inevitable. The adaptation pathways approach illustrated for Venice has global relevance and thinking through potential pathways is an important step towards practical and realistic coastal adaptation given the long-term commitment to SLR and the uncertainty in its rate.

Venice has faced transformation and adaptation to a changing environment throughout a millennial history, but future challenges are unprecedented in terms of pace of change and structural dimension. While the historical evolution of Venice and its lagoon was largely dependent on local cultural and economic capacity, it now requires solutions relying on large-scale cooperation and depending substantially on drivers acting beyond local control.

Taken together, our results show that adaptation pathways provide a decision-relevant framework to clarify which long-term choices Venice will face as sea level continues to rise. Each feasible strategy preserves a distinct configuration of economic, environmental, social and cultural values, and the narrowing of the solution space with rising SLR highlights the need for early judgement on which of these values future communities aim to retain. For decision makers, the pathways approach does not prescribe an optimal option; rather, it makes explicit the trade-offs and the adaptation tipping points at which transitions become unavoidable. This enables choices to be made with full awareness of the gains and losses across competing interests, and of the lead times required for large-scale interventions. More broadly, Venice illustrates how pathways can guide robust long-term coastal planning under deep uncertainty, helping societies align present decisions with the values they wish to preserve in the centuries ahead.

# Methods

## Estimates of sea-level rise and land elevation

The SLR values in Fig. 3 and in the text are based on state of the art projections assessed in the 6th Assessment Report of the IPCC[15]. Values specific for Venice can be extracted from public repositories providing consistent values with minor differences that are not relevant for this study[8,58–61].

While these data approximately consider land subsidence in the historical city centre, where values in the last 50 years, after the regulation of groundwater use, are between 1 and 2 mm year$^{-1}$[62], subsidence increases across the lagoon up to 4 to 6 mm/year in poorly consolidated salt marshes[38,63]. This analysis assumes that the effective regulation of groundwater use continues. Hence, land subsidence is due to long term natural components largely due to the consolidation of the shallow subsurface sediments, i.e. the Holocene depositional units, and its variability reflects the geological setting of the lagoon[64]. Extrapolating to the next centuries the current rates of about 1-2 mm/year for the historic centre and 3-4 mm/year for the lagoon is plausible, but anthropogenic activities (e.g. construction of dikes or dams) could locally affect it. Therefore, for low emission scenarios, as long as the SLR velocity is in the same order of magnitude as the land subsidence, the relative SLR footprint in Venice and its lagoon will be heterogeneous[38] with substantial implications for the preservation of the lagoon ecosystems and of monuments.

Timing of global SLR milestones up to 5 m until 2300 are accessible through the same website[58] and are considered adequate in this study for the long term estimates based on evidence that past (neglecting land subsidence interannual variability) and future long term trends in Venice are very similar to global values[7,65,66]. Among other data used for this study, the IPCC AR6 WG1 chapter 9[15] reports that global mean sea level will rise between 0.3 and 3.1 m and between 1.7 and 6.8 under SSP1-2.6 and SSP5-8.5 by 2300, respectively, and in the latter case up to 16 m considering possible contributions from marine ice cliff instability. Further studies, based on different methods and published after the 6th IPCC Assessment Report have revisited low-likelyhood-high impact scenarios to 2300 without changing significantly these values[30,31].

The map shown in Fig.1 is a digital terrain model (DTM) provided by the Veneto Region (https://idt2.regione.veneto.it/idt/downloader/download), which is intended to illustrate the general morphological setting of the area around Venice. The DTM is based on surveys carried out in the 1990s and the data refer to the Italian national geodetic network, which in turn refers to the MSL determined in the 1940s. Actually, land subsidence and SLR have led to a further reduction in ground elevation. Land subsidence, acting with a large spatial variability ranges from negligible values up to 1 cm/year[64,67], has contributed up to 20 cm in some areas, while the SLR implies a uniform negative decrease of 1.2 mm/year[8], i.e. about 10 cm compared to the 1940s. Practically these two sources imply a negative systematic error with a magnitude of about 25-30 cm, which is too small to be relevant in this analysis.

The fraction of historical centre flooded as a function of the sea level are computed using the data provided by Insula spa (http://smu.insula.it/index.html).

## Land uplift by seawater injection: values, technical details and costs

Fluid injection into the subsurface is used worldwide for multiple purposes (managed aquifer recharge, enhanced oil recovery, geologic sequestration of $CO_2$ and wastewaters, and underground gas such as $CH_4$, $H_2$ storage) and it is always accompanied by an uplift of the land surface above the injection facilities. State-of-the-art 3D hydro-geomechanical modelling shows that using 12 wells located on a 10-km diameter circle around the Venice city centre to inject seawater into the deep aquifer system below the lagoon between 600 and 1000 m depth can produce an uplift of approximately 25-30 cm[21]. With the planned well locations, the area benefiting by the uplift encompasses the Venice historic centre, Murano, and other islands around Venice. A proper management of the injection rates, combined with the large depth of the targeted aquifers, would ensure a uniform uplift, with displacement gradients that are substantially smaller than those caused by land subsidence over the past century, precluding risks for building instability[20]. The maximum overpressure would occur well below the fracturing threshold. A thick clay unit revealed by seismic surveys and borehole lithostratigraphy, will preclude any propagation of the saline water toward the freshwater aquifers located above 350 m depth. Costs, initially estimated to be 0.08G€ for construction of the wells and 0.1G€ for operating them for 10 years[68], have now risen to a total in the range 0.3-0.4G€ considering the increased costs of the drilling, equipment, and energy costs over the last 10 to 15 years. With the present market prices, annual maintenance and operating costs, including electricity, seawater treatment, and personnel is estimated in 0.02G€/year.

## Extreme sea-level events and height of coastal defenses

In Fig.2 elevation profiles have been utilized to outline the primary coastal defenses located at the boundaries of the Venice lagoon. Elevation datasets refer to the DTM with 1 and 2 m ground resolution resulting from LiDAR scanning on an aerial platform acquired by the Ministry of the Environment and the Protection of Land and Sea under the Extraordinary Environmental Detection Plan (PST-A). The datasets are available from the Ministry of the Environment and Energy Security (https://gn.mase.gov.it/portale/en/home and https://sim.mase.gov.it/portalediaccesso/mappe/#/viewer/new).

Dunes in the areas without artificial protection have a level of about 9 m above MSL, although a detailed inspection reveals the presence of small isolated gaps where the maximum elevation is between 2 and 3 m. The height of the current defenses along the barrier islands is approximately 5 m. Currently, dykes and riverbanks approximately 4-meters high separate the lagoon from the adjacent polders. Therefore, a head height of 5 m above mean sea level is sufficient to prevent wave overtopping during major storms and damage to inhabited areas.

These values of the height of the coastal defenses are consistent with other estimates. The 100-year return level has been estimated to be approximately 1.50 m[69], but excluding the contribution of astronomical tides and of interannual to seasonal sea-level variability. During major past events, the contribution of the interannual to seasonal sea-level variability never exceeded 20cm. Considering a further addition of astronomical tide (maximum of about 50cm) confirms that 3 m are a reasonable upper limit for sea-level maxima, which with a 60% addition to prevent wave overtopping would lead to a height of 5m.

The future increase of extremes during storms will be mostly produced by SLR[70], with changes of storminess playing a minor role[71]. The effect of SLR on astronomical tides will depend on the future large scale adaptation strategy[72]. Preserving the present coastline of the Adriatic will lead to a decrease of the amplitude of astronomical tides, while allowing a free expansion of the sea inland will increase the amplitude of the diurnal components. As a consequence, it has been estimated that a 2-meters SLR might lead to a 5% increase or decrease of the amplitude extreme events[72].

In conclusion, 3-meters high ring dikes inside the lagoon, where wave propagation from the sea is prevented by barrier islands, and 5-meters high dams across the inlets and embankments along the barrier islands, both with respect to the mean sea level, are expected to provide sufficient protection.

The height of embankments separating the lagoon from the surrounding polders would be different depending on whether the closed lagoon or the ring-diking strategy is adopted. In the former case, the water level inside the lagoon will remain at its present level and the increase of the embankments will not be required. In case of ring-diking the water level inside the lagoon will follow the SLR and the height of the embankments should match that of the dikes. However, the protection of the polders will require an overall revision of the coastal protection and hydraulic drainage system at regional level, beyond the adaptation of the Venice lagoon to SLR, whose discussion is beyond the scope of this article.

## Pluvial and river flood risks

Although this study focuses on long-term sea-level rise, pluvial and riverine inputs represent an additional source of flooding that becomes relevant whenever the lagoon–or parts of it–is temporarily (during MoSE closures) or permanently (under ring-dike or closed-lagoon strategies) isolated from the sea.

Recent observational analyses for Italy show suggestive evidence of increasing heavy rainfall intensity, despite spatial heterogeneity in the trends[74,75]. Future projections indicate a widespread intensification of precipitation extremes across northern and northeastern Italy under high-emission scenarios[76].

Intense precipitation and river inflows can raise water levels inside a closed lagoon independently of the sea level. Hydrodynamic simulations and observations indicate that rainfall over the lagoon surface and river discharge may increase lagoon water levels by several centimetres during MoSE closures[12,33,77]. Comparable risks would arise under the closed-lagoon strategy and, to a lesser extent, under ring-diking. In the latter case, river flooding would be irrelevant, and only precipitation falling on the protected areas would need to be managed.

Installing pumping systems is an effective way to reduce pluvial and river-flood risks. For a fully closed lagoon, a first-order engineering estimate indicates that managing precipitation and river inflows during extreme events requires a peak pumping capacity of approximately 1,000 $m^3 s^{-1}$ under present climate conditions. This estimate is obtained by summing the current estimated river peak discharge[78] and the contribution of the maximum daily precipitation from observational gridded data in the area around the lagoon[75]. Assuming a 20% increase in precipitation extremes by the end of the century under a very high-emissions scenario, the required peak pumping capacity would rise to roughly 1200 $m^3 s^{-1}$.

Pumping requirements would be substantially lower for the ring-dike strategy because the contributing surface is much smaller and river inputs are excluded. Incorporating these operational needs into future assessments would imply increasing long-term pumping-system costs by a factor of 2 to 3 for both strategies.

## Indicative cost estimates of the strategies and of the corresponding measures

Indicative capital costs for the proposed measures and adaptation pathways are estimated using unit costs from previous literature, international analogs and expert judgement (fig.7). This analysis is a first approximation, which has the high relevance of being the first to attempt a systematic assessment of the order of magnitude of the broadest conceivable set of long term adaptation strategies. Unless specified, all amounts presented here are adjusted for inflation to 2024 prices. Due to the city's historical and cultural importance, as well as its unique geography, costs in Venice tend to be much higher than comparable experiences elsewhere. Our estimate is subjected to this systematic uncertainty and might be a systematic underestimate of order up to 50%. While cost will be a determinant factor in the realization of individual strategies, it is important to note that our analysis aims at providing indicative estimates rather than precise values mainly in order to compare the costs

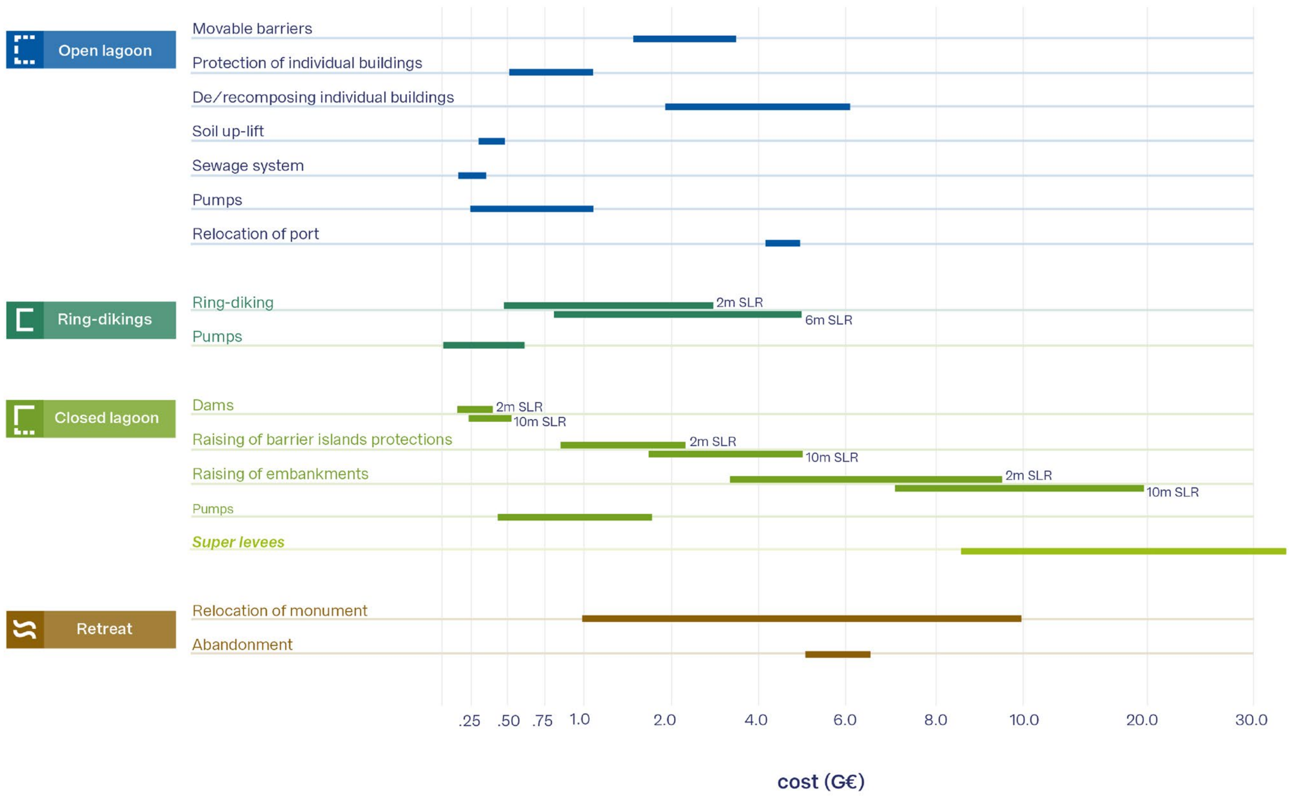


**Fig. 7**. Indicative costs of the measures (in G€). Each bar extends from the minimum to the maximum estimated cost. For the ring-diking and closed lagoon strategy, the costs corresponding to 2 and 6 m and to 2 and 10 m, respectively, are shown.

| SLR (cm) | yearly duration of closures (months) | Total cost (G€/year) |
|---|---|---|
| 50 | 2 | 0.015 - 0.031 |
| 75 | 6 | 0.044 - 0.093 |
| 120 | 10.5 | 0.077 - 0.162 |

**Table 1**. Total costs associated with the operation of the MoSE system. total duration of closures is based on literature[7]. Total costs include operation of the barriers and disruption of port activities.

of the different options. As a reference, all the estimated costs could be compared to the 6G€ total cost for the construction of the MoSE system[13].

### *Open lagoon*

Maintaining the open lagoon includes the costs of operating MoSE and of the implementation of the pumping and sewage systems required by frequent closures of the lagoon. The increase of MoSE costs with SLR are summarised in Table 1. They are obtained adding operating costs (between 30 and 300 K€ per closure) to costs caused by disruption of ship traffic (average 215K€ per closure[79], assuming daily durations and that prolonged multi-day closures are equivalent to the sum of individual closures[13]. Total estimates would depend on the rate of SLR. As an order of magnitude estimate, one could assume costs linearly increasing over 75 years until there is a 6 month annual duration of closures, with total costs in the range 1.5 to 3.5 G€.

Costs (not considering maintenance) of pumping systems vary between 0.47 and 2 M€/m3/s and depend on factors such as length of pipes, distance to source area, motor type and drainage area[80]. Assuming that the pumping system is designed to respond to the maximum peak flow of the Venice lagoon tributaries and sub-basins (a reference value of 344 m$^3$/s[78] and to the precipitation inside the lagoon (about 200 m$^3$/s in case of a 50mm daily precipitation), the construction of the pumping system for a lagoon-scale system would cost from 0.25 to 1.1G€.

A wastewater treatment plant currently under construction for an area of 150,000 people in Trento in Northern Italy, is estimated at a cost of 0.113G€, with an expected operational cost of 1.3M€/year considering current costs in the region[81]. These costs are roughly consistent with the upper limit of the estimated costs for conventional sewage systems (USD 770 per inhabitant at 2010 prices[82]. Considering the complexity of creating a collection system in the historical centre, the unit costs can be multiplied by at least a factor of two with respect to the cost sustained in Trento, reaching a cost in the order of 0.3G€, including operating it for 75 years. Dry-proofing individual buildings (e.g. protective shields, external impervious coating, etc.) is already ongoing in Venice. Costs vary between USD9,000 and USD23,000/building (2016 prices) in developed countries[80]. Applying this strategy to the 2740 buildings below an elevation of 1 m in Venice's historical centre would thereby cost from 0.03G€ to 0.08G€. Maintenance costs per year are estimated at 1-3% of the investment cost[80]. This is a low cost option compared to other accommodation measures that would be needed to extend the lifetime of the open lagoon strategy.

In 2022, a glass barrier was installed to protect St. Mark's Basilica. The 150m-long and 1.3m-high barrier is reported to have cost 5.3M€[83] and is equipped with a pumping system. Taking the same unit cost and height as the barrier protecting the Basilica, deploying this measure to protect exposed (below 1m elevation) buildings of cultural significance would cost 1.1G€ (excluding maintenance costs). In this calculation, 245 buildings are considered and it is assumed the glass barriers align with respective building perimeters.

The reconstruction and raising of existing buildings is a much more expensive process. An estimate for building types in Los Angeles[73], provides unit costs per building footprint that highly dependent on the type of structure, with "masonry structure with slab-on-grade" being the most fitting category to buildings found in Venice. Costs in Table 2 consider an average building footprint of about 1363 m$^2$ (calculated using OpenStreetMap features). An important caveat of these estimates is the extremely soft subsurface layers, the complexity of structures and foundations in Venice, which would lead to much greater costs than in other cities. It is therefore plausible to apply a factor 2 or larger to the costs in Table 2.

### *Ring-diking*

Two different ring diking configurations are considered. The first comprises three ring dikes around (1) Venice's historical centre and Giudecca, (2) Murano and (3) Burano-Mazzorbo-Torcello. The second configuration covers a much larger perimeter to enclose Venice as well as developed surrounding islands, connecting the dike to the Lido barrier island. The depth near Venice's historical centre is assumed to be deeper than in the rest of the lagoon at 4 m compared to 2 m for the other dikes. A hydraulic head of 3 m is targeted for each dike.

Energy costs of pumping $C_{PE}$ would increase with SLR because of increasing difference of water level between the two sides of the dikes:

$$C_{PE} = c\frac{\rho g V H}{\phi\, 3.6 \cdot 10^6}, \tag{1}$$

where $\rho$ is water density (about 1030 $Kg/m^3$), g is gravity (9.8 $m/s^2$ ), $V$ is the total annual precipitation (800mm), $H$ (is the level difference, $m$), $\phi$ the pump efficiency (0.7). Assuming a cost of 0.2€/kWh and a maintenance cost of 3% of the capital cost (ignoring SLR related compounding factors such as salinity, corrosion and more frequent operations) shows that the former ones are a minor fraction of the latter ones (in the range from 5% to 20%). Table 3 shows the dike and drainage area characteristics and associated construction and pumping (including energy and maintenance) costs based on available estimates[23].

### *Closed lagoon*

The permanent closure of the lagoon requires the construction of stationary barriers across the present lagoon inlets, the raising of barrier islands to prevent encroachment and possibly of the whole system of canal banks around the lagoon separating it from the surrounding polders.

The unit cost of sea dikes for Italy is estimated at 4.09-11.25 M€/km/m[23] , adjusted to 2024 prices. Yearly maintenance costs are assumed to be 3% of construction costs. Table 4 presents estimated costs of the permanent barriers with a 5-meter hydraulic head for different SLR values.

A closed lagoon strategy might require elevating the banks separating the lagoon from surrounding polders either to avoid "backdoor" flooding of the lagoon or flooding of the polders, depending on regional adaptation strategy. A 5m-high dike over the 120 km length of the lagoon perimeter would cost up to 20G€[23] in case of a 10-meter SLR. This cost would be about 90% lower if a 3-meter head and the present water level inside the lagoon are assumed. The cost for a stone embankment of the same height stretching 28.5 km on the Lido, Pellestrina barrier islands and the Sottomarina peninsula to the South of the lagoon can be estimated in a similar way in the range 0.83 – 4.81 G€ depending on SLR. Pumping costs of the closed lagoon strategy (estimate in the range 0.44-1.78G€) would be much higher than for the ring-diking strategy as the water level of the whole should be kept fixed. The coastal offshore front of the lagoon could also be considered for a "super-levee". An example has been conceptualised in Tokyo, Japan[25]. This structure would be much wider (a width equal to 30 times its height) and

| raise buildings by (m) | Unit cost (USD/ft$^2$) | Total cost for 35% of buildings (G€) | costs for all buildings (G€) |
|---|---|---|---|
| 0.6 | 88 | 1.01 | 2.83 |
| 1.2 | 91 | 1.05 | 2.93 |
| 1.8 | 96 | 1.10 | 3.09 |

**Table 2.** Total Costs of raising existing buildings. Unit costs (column 2) in UST/ft at 2010 prices are extracted from literature[73] and converted to G€ 2024 prices in columns 3 (35% of buildings) and 4 (all buildings in the historical centre).

| CONSTRUCTION COSTS | | | | | | |
|---|---|---|---|---|---|---|
| **ring diking area** | **length** | **area** | **present SL** | **2 m SLR** | **4 m SLR** | **6m SLR** |
| | (km) | ($km^2$) | (G€) | (G€) | (G€) | (G€) |
| Venice | 15.8 | 10.3 | 0.45-1.24 | 0.58-1.60 | 0.71-1.96 | 0.84-2.31 |
| Murano | 5.3 | 1.7 | 0.11-0.30 | 0.15-0.42 | 0.20-0.54 | 0.24-0.66 |
| Murano-Mazzorbo-Torcello | 8.9 | 3.1 | 0.18-0.50 | 0.25-0.70 | 0.33-0.90 | 0.40-1.10 |
| large | 36.2 | 99.3 | 0.74-2.04 | 1.04-2.85 | 1.33-3.66 | 1.63-4.48 |

| PUMPING (energy and maintenance) COSTS | | |
|---|---|---|
| **ring diking area** | **area** | **from present SL up to 6m SLR** |
| | ($km^2$) | (G€) |
| Venice | 10.3 | 0.02-0.07 |
| Murano | 1.7 | 0.003-0.01 |
| Murano-Mazzorbo-Torcello | 3.1 | 0.005-0.02 |
| large | 99.3 | 0.16-0.65 |

**Table 3**. Ring dikes with indicative construction (top) and pumping costs (bottom). Each dike has a head of 3 m, for a total height obtained by adding head, SLR and a depth of 4 m around Venice's historical centre, and 2 m in the other dikes. The large perimeter ring dike corresponds to a separate configuration that would enclose Venice's historical centre as well as other developed areas. Different SLR conditions are considered only for construction costs, as they have a negligible effect on pumping (including energy and maintenance) costs. Pumping costs are computed to cover a 50 years duration.

| CONSTRUCTION COSTS | | | | | | | |
|---|---|---|---|---|---|---|---|
| **inlet** | **depth (m)** | **length (m)** | **present SL** | **2 m SLR (G€)** | **6 m SLR (G€)** | **10 m SLR (G€)** |
| Lido 1 | 8 | 420 | 0.02-0.06 | 0.03-0.07 | 0.03-0.09 | 0.04-0.11 |
| Lido 2 | 8 | 440 | 0.02-0.06 | 0.03-0.07 | 0.03-0.09 | 0.04-0.11 |
| Malamocco | 14 | 540 | 0.04-0.11 | 0.05-0.13 | 0.06-0.15 | 0.06-0.18 |
| Chioggia | 8 | 550 | 0.03-0.08 | 0.03-0.09 | 0.04-0.12 | 0.05-0.14 |
| Total | | | 0.12-0.32 | 0.13-0.37 | 0.16-0.45 | 0.20-0.54 |
| bottomrule embankments | | | | | | |
| barrier islands | | | 0.58-1.60 | 0.83-2.22 | 1.3-3.53 | 1.75-4.81 |
| lagoon borders | | | 2.45-6.75 | 3.44-9.45 | 5.40-14.9 | 7.36-20.02 |
| bottomrule | | | | | | |

| PUMPING (energy and maintenance) COSTS | | |
|---|---|---|
| | **area ($km^2$)** | **from present SL up to 6m SLR (G€)** |
| whole lagoon | 550 | 0.44-1.78 |

**Table 4**. Indicative construction costs for dams at lagoon inlets, embankments along the barrier islands and the borders of the lagoon assuming a head of 5 m and SLR of 2, 6, 10 m. The costs are based on the total height, which is estimated adding depth, SLR and head

therefore significantly more expensive than a simple dike and reliant on available space. The cost of a super-levee of roughly the same length (44 km) in Edogawa was estimated at 16.91G€[25].

The cost associated with the relocation of Venice's port is derived from the unit cost of USD millions 16.6/km2/m[50]. This value is based on costs reported for the Maasvlakte2 development in Rotterdam and includes land reclamation and construction of infrastructure. The current Port of Venice covers an area of 20.45 km2. For a maximum depth of 13.5 m the cost of relocation is estimated at 4.1G€. For an additional 1.2 m depth, the cost increases to 4.47G€. Costs for sewage treatment are to be considered as part of the closed-lagoon strategy, as it was described for the open-lagoon strategy.

### *Relocation*

The relocation of historical monuments is a costly and complex operation. The example of Abu Simbel in 1968 cost between M$ 40 and M$ 70, which corresponds to 0.34G€ - 0.56G€ in 2024[26]. This was a relatively small-scale operation compared to the extent of relocation that would be required in Venice. Adopting the cost of Abu Simbel to the relocation of 3 to 30 buildings would therefore result in a range from 1 to 10G€. However, this is a very uncertain estimate, because of unknown technical issues and dependence on the number of considered buildings.

*Abandonment*
Low direct costs can be assumed for the abandonment strategy, though the removal of environmentally damaging material (e.g. oil) would need to be considered. However the relocation of residents would have relevant costs. An example is the scheme offered by the Austria government (Relocation as adaptation to flooding in the Eferdinger Becken, Austria), which offered 80% of their house value to people as compensation if they agreed to relocate from areas prone to floods. Considering market price a 100m$^2$ apartment in Venice would have a cost of about 0.33M€, which would bring a compensation costs of 0.26M€ per each household. Considering 25,000 households in total would imply a total compensation cost of about 6.5G€. If, alternatively, a cost of 3 x GDP/capita (approximately 35K€) per person moved is assumed[27], the cost would be about 5.25G€ considering 50,000 inhabitants. Furthermore, abandonment would imply the cancellation of the tourism sector, which has presently an annual turnover of approximately 1G€[84].

## Data availability

Sea-level projection data used in this study are publicly available from the following repositories: Zenodo https://doi.org/10.5281/zenodo.6382554, Zenodo https://doi.org/10.5281/zenodo.5139890, and the IPCC AR6 Data Distribution Centre (Distilled and Bias-Corrected Sea Level Projections; https://doi.org/10.26050/WDCC/AR6.IPCC-DDC_AR6_Sup_DistBC. Code and associated data are described in https://doi.org/10.5194/gmd-16-7461-2023 (see section "Code and Data Availability"). Land elevation datasets of the areas surrounding the Venice Lagoon and of the lagoon islands used in this study are publicly available from the Italian Ministry of the Environment and Energy Security via the National Geoportal https://gn.mase.gov.it/portale/en/home and the Spatial Data Access Portal https://sim.mase.gov.it/portalediaccesso/mappe/#/viewer/new. For Figure 1 and related analyses, land elevation data were extracted from a Digital Terrain Model (DTM) provided by the Veneto Region https://idt2.regione.veneto.it/idt/downloader/download. High-resolution elevation datasets of the Venice lagoon boundaries with 1 m and 2 m ground resolution (Figure 2 and associated text), derived from airborne LiDAR surveys, were acquired by the Italian Ministry of the Environment and the Protection of Land and Sea under the Extraordinary Environmental Detection Plan (PST-A). These datasets are publicly accessible via the portals of the Italian Ministry of the Environment and Energy Security listed above.Ground elevation data of the Venice historical centre used in this study to compute the fraction of flooded area are publicly available from the RAMSES project promoted by the Municipality of Venice and implemented by Insula S.p.A., accessible via the Insula S.p.A. portal http://smu.insula.it/index.html. Information used for cost estimates was obtained from the peer-reviewed scientific literature cited in the manuscript.

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## Author contributions

PL: coordination, conceptualization, discussion, writing of the whole text, graphics of figures 3, 4, 5 and 6 VDF: conceptualization, discussion and description of measures and strategies and writing of the corresponding text UP: computation of costs estimates and writing of the corresponding text LT: assessment of the elevation of ground and defence systems, production of figures 1 and 2 GLC: conceptualization, discussion, analysis of sea-level rise RJN: conceptualization, discussion, methodology for cost estimates, contribution to overall writing PT conceptualization, discussion and detailed cost estimate of the measure for ground elevation WC, RC, CG, JH, AS, ATV, GU : conceptualization and discussion MH: conceptualization, discussion, graphics of figures 4,5,6

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## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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