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ORIGINAL ARTICLE

Boon and burden: economic performance and future perspectives of the Venice flood protection system

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Abstract

Sea-level rise (SLR) and flooding are among the climate change stressors challenging human society in the twenty-first century. Many coastal areas and cities are implementing innovative solutions to mitigate flood risks and enhance resilience. Venice has recently developed a system of storm surge mobile barriers, known as the MoSE (Modulo Sperimentale Elettromeccanico *or* Experimental Electromechanical Module). This study aims to investigate the economic viability of MoSE operations in light of the potential future evolution of SLR. To conduct a cost-benefit analysis, a system dynamics model is utilised to assess the impact of MoSE operations on economic and residential activities of Venice and its port. Simulations are conducted until the end of the century, considering two SLR scenarios. The results suggest that the economic benefits largely outweigh the combined costs of investment and foregone port revenues resulting from the MoSE closures. Nevertheless, the increasing number of closures due to SLR seriously challenges the viability of the infrastructure in the medium to long term. Even more importantly, very frequent closures will have serious impacts on the quality of the lagoon ecosystem. These findings suggest a revision and stronger integration of the city's safeguarding strategies, including the increase of the MoSE closure level officially set at 110 cm, and other coordinated interventions, such as sewer system consolidation.

Keywords Venice · Sea-level rise · Storm surge barriers · Management strategies · Cost-benefit analysis · Economic valuation

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Introduction

Sea-level rise (SLR) and flooding are among the most important climate change stressors challenging human society in the twenty-first century. Coastal flood risk has escalated in many locations due to SLR, storm surge, local subsidence, and coastal development activities. According to the Special Report on Ocean and Cryosphere in a Changing Climate (IPCC 2019) and the Sixth Assessment Report (IPCC 2022) of the Intergovernmental Panel on Climate Change (IPCC), global mean sea level (GMSL) rose by 17 cm over the twentieth century and keeps rising at an accelerating rate (Dangendorf et al. 2019; IPCC 2022).

Low-lying coastal regions, where approximately 900 million people reside, produce approximately US$ 1 trillion of the world's wealth (Kirezci et al. 2020). Recently, the IPCC estimated that once-in-100-years coastal floods might affect between 176 and 880 million people by 2100 (under RCP 8.5, the high-risk climate change scenario of the IPCC) and result in economic losses ranging between US$ 8813 and 14,178 billion in terms of aggregate asset value (IPCC 2022). Kulp and Strauss (2019) reported that coastal cities such as Ho Chi Minh City (Vietnam), Bangkok (Thailand), Shanghai (China), Mumbai (India), Jakarta (Indonesia), Alexandria (Egypt), and Basra (Iraq) are projected to be inundated by 2100, assuming SLR levels consistent with the RCP 8.5 scenario. Therefore, addressing SLR, along with coastal flooding, is one of the most important challenges of the twenty-first century.

The Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015) emphasises the need for a substantial reduction in potential disaster damages to critical infrastructures and essential services by enhancing their resilience. Therefore, coastal defence infrastructures (either green or grey ones) are essential for addressing future SLR and flooding caused by climate change. Many coastal areas and cities have adopted innovative technological measures that involve constructing flood barriers (Mooyaart and Jonkman 2017; Tognin et al. 2021). Examples of these can be found in the River Scheldt Estuary (the Netherlands), St. Petersburg (Russia), the River Thames (UK), New Orleans (USA), Galveston Bay (USA), Shanghai (China), and Venice (Italy).

Venice, along with its lagoon, is recognised as a UNESCO World Heritage Site due to its unique and outstanding cultural, environmental, historic, artistic, and landscape values (Lionello et al. 2021). The Venice Lagoon represents an extraordinary case of ecosystem alteration in the Anthropocene era. Over the last 16 centuries, the lagoon system and the surrounding land have undergone significant anthropogenic alterations, for strategic defence of the city and the preservation of its lagoon: diversions of major tributary rivers outside the lagoon to prevent sedimentation, barriers to protect the islands from storm surges, jetties at inlets to maintain port navigation, land reclamation for expanding urbanisation, and massive extraction of groundwater for urban and industrial development (Madricardo et al. 2019).

Flooding due to high tides, known as the *acqua alta* (high water), is an endemic feature of the lagoon that threatens the preservation of the city and disrupts the daily lives of residents and tourists. The frequency of these extreme events has steadily increased over recent decades, and is predicted to grow even more into the future (Umgiesser 2020; Umgiesser et al. 2021).

Recognising the importance of protecting the city, the lagoon, and its watershed from flooding and other natural and anthropogenic hazards, the Italian government established a legal framework, known as the Special Law for Venice (Munaretto et al. 2012). As provided by the Special Law, a system of storm surge mobile barriers, known as the MoSE (Modulo Sperimentale Elettromeccanico *or* Experimental Electromechanical Module), has been built and has recently started operating in a preliminary experimental mode. During *acqua alta* events, the system protects the city by isolating the lagoon from the sea for the entire duration of the flood (Mel et al. 2021). The system consists of 78 floating gates with hinges at the bottom of the inlet channels. When activated, the barriers interrupt the connections between the lagoon and the sea at the three inlets of Lido, Malamocco, and Chioggia (see Fig. 1). The MoSE system includes locks to maintain the connectivity of the port with the open sea, allowing ships to cross the barriers even during closures, but these locks are not operational yet (Tomasicchio et al. 2022).

The most recent available figure concerning the expected total investment cost of the MoSE project exceeds € 6 billion. In addition, even though an official estimate is still missing, the operational costs are expected to be in the order of several tens of millions of euros per year.

In general, the anticipated benefits of the MoSE operation primarily revolve the physical safeguarding of the historic city and its unique cultural heritage. They also include immediate and direct economic benefits in terms of avoided damages to real estate and economic activities, as well as enhancements to the everyday life of residents. However, these benefits come at a cost, as MoSE closures negatively affect the activities of the port, which is located within the lagoon. Port entries and exits are delayed and ships incur additional costs when docked in the port or waiting outside the lagoon (Fontini et al. 2010). According to Vergano et al.

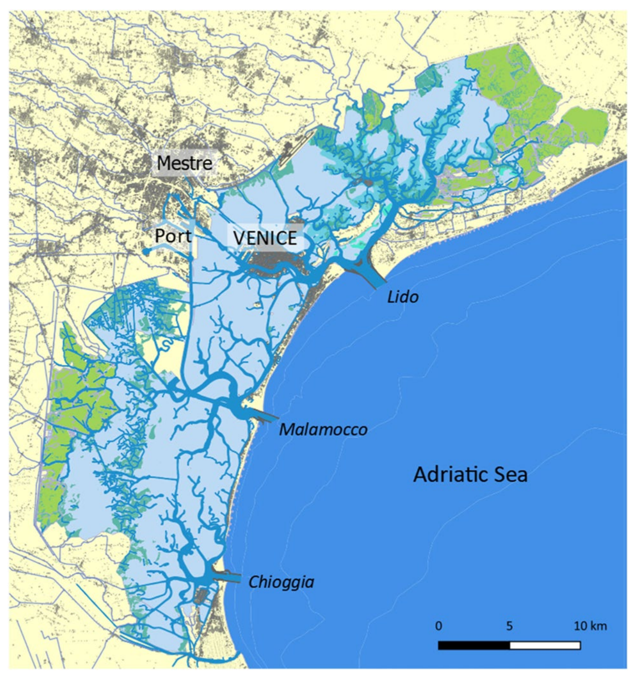

Fig. 1 The Venice lagoon, with the location of the city, its port, the mainland city of Mestre, and the three inlets connecting to the Adriatic Sea (Lido, Malamocco, and Chioggia), where the MoSE system operates

(2010), the direct costs to ship traffic (i.e. longer waiting times for entering the lagoon and accessing the harbour) associated with MoSE operations range from € 348,000 to € 1.3 million a year. Moreover, a negative impact is expected due to the limitations that the barriers pose on the exchange of water between the lagoon and the sea during closures. This may have a detrimental effect on water quality in case of frequent closures and hinder sediment accumulation on the salt marshes, thus limiting the ecosystem's capacity for vertical accretion and survival amidst rising sea levels (Leonardi 2021; Tognin et al. 2021; Bellafiore et al. 2014; Munaretto et al. 2012).

Despite the extensive body of literature examining interventions for the safeguarding of Venice, only a limited number of studies investigate the extent to which MoSE operation is economically viable over a long time horizon when considering its impact on the city economy and port activities (Caporin and Fontini 2016; Cellerino 1998; Fontini et al. 2010; Nunes et al. 2005; Vergano et al. 2010). This paper aims to contribute to this literature by proposing a novel approach for cost-benefit analysis (CBA) developed in a system dynamics modelling environment. This approach allows to secure adequate consideration of the dynamics of costs and benefits emerging from the interactions between city's economy and port activities and the water levels characterised by two tidal peaks per day, subject to astronomical and meteorological drivers and future scenarios of climate change (Ahmad et al. 2016; Hsu 2012; Nguyen et al. 2017; Shih and Tseng 2014; Tu et al. 2023; Wang and You 2021). In particular, this paper analyses how costs and benefits may accumulate until the end of the century under two SLR scenarios and answers three main research questions: (i) How do the benefits for the city compare to the investment and operating costs of the MoSE system? (ii) How do the lost revenues for the port compare with the benefits for the city? and (iii) Are there foreseeable tipping points before the end of the century in terms of functionality of the MoSE (i.e. an excessive number of closures of the barriers due to SLR)?

The answers to these questions allow for broader and conclusive considerations concerning the contribution that the system of mobile barriers can provide within the complex set of policies, measures, and infrastructures for safeguarding Venice.

Methods

The model

In line with the previous economic literature analysing the Venice case (Caporin and Fontini 2016; Cellerino 1998; Nunes 2005), the model focuses on the city's economy and the port activities.

To achieve the stated objectives, we have developed a system dynamics model comprising three main modules: MoSE management, City, and Port. The model calculates the direct costs associated with the city and the port, while not considering losses and indirect effects on broader economic systems, such as impacts on activities connected to the port or tourism.

Figure 2 presents the simplified structure of the model, and we provide comprehensive documentation in the supplementary material available online.

The model operates with a time step of 6 h, which corresponds approximately to the two tidal minimum and maximum values per day. Both historical records and future projections adopt that structure of the time series. The values provided by these time series are used to calculate the *Tide forecast* variable by introducing a forecast error as random noise, varying within a ±20-cm interval. This reflects the current accuracy of the official forecast service. The MoSE system is activated once the resulting forecast exceeds the predefined closure threshold. This procedure replicates the current criteria adopted by the appropriate administrative authority operating the MoSE (see Commissario Straordinario MoSE at https://www.commissariostraordinariomose.it/). We apply a charge for each closure, which includes both energy and labour costs, based on informal communication from the competent authority. Given the lack of official information concerning these costs, we apply sensitivity analysis to explore their effects on cost-benefit analysis. We do not include in the calculations the total annual maintenance cost as it remains unknown, but we take it into consideration in the discussion of the results obtained.

The model estimates potential costs to the city from damage to buildings and costs incurred to residents and tourists by applying damage functions whose values depend on the lagoon water levels. Each calculation corresponds to an observation of water levels affected by tidal cycles. When MoSE is activated, potential damages to the city associated with high tides are either partially or entirely avoided, depending on the water level at which the barriers are closed. The lowest areas of the city, about 2% of the total area, are flooded when the water level rises to 90 cm above mean sea level. The extent of flooding increases as the water level rises, and at a level of 200 cm, more than 90% of the city is flooded. The most severe flood event was recorded on November 4, 1966, when the water level reached 194 cm and the second was on 12 November 2019, with 187 cm. The model considers the historical city only, because the information needed for damage estimations is not available for smaller islands. Assuming that the characteristics of those islands are statistically similar to those of the city centre, we can estimate the values obtained for the city by comparing the built surface area of the city centre with that of the other islands (Murano, Burano, Torcello, Vignole,

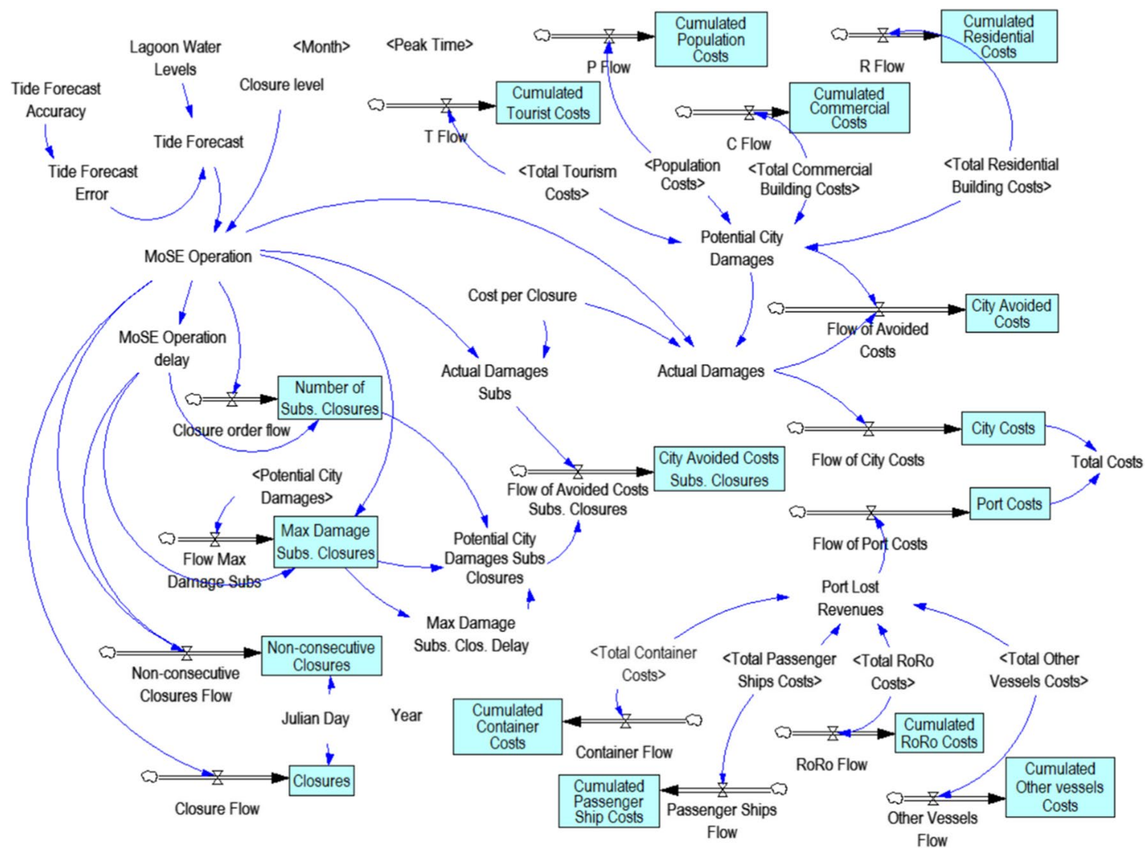

Fig. 2 Stock and flow diagram of the core functions of the MoSE model (modules on city damages, tourism, and port lost revenues are presented in the supplementary materials)

and Sant'Erasmo). This estimation suggests that the values obtained for the city can be increased by approximately 20% to cover the whole lagoon.

Damage to the buildings is calculated for each event by considering the cost of repair work to building structures. The magnitude of these costs was assessed through empirical estimates using expert judgment sources from technicians and practitioners in the city. Based on the information gathered, it is estimated that the replacement of damaged internal and external doors occurs on average every 7.5 and 15 events, respectively. Re-plastering of internal and external walls is typically performed on average after every 5.7 events to which these elements have been directly exposed (see supplementary materials for details about the procedure).

Revenue losses in the tourism sector have been estimated by considering the impact of *acqua alta* events on overnight stays of tourists and the 1-day visits of excursionists (i.e. the visitors who do not stay in the city over night). These estimates were derived from the available data on average expenditures (€181 and €47, respectively; see supplementary materials for details), along with monthly arrival statistics prior to the COVID-19 pandemic. By comparing water levels and tourist statistics, we developed the model by considering that only extreme events (i.e. those ≥ 140 cm which flood 59% of the city surface) are widely communicated by international media and consequently cause a decrease in arrivals during the months following the flooding.

In accordance with the above description, the system dynamics model in Fig. 2 presents two stock variables: *City Costs* and *City Avoided Costs*. When the forecasts are below the closure threshold, the barriers are open, and some areas with low elevation may be flooded. The damage functions implemented in the model calculate damages, which are accumulated as *City Costs*. When the forecast is above the threshold, gates are closed and the same functions are applied to the water level that would be reached without the MoSE and the results are accumulated in the stock variable *City Avoided Costs*. In case of closure, some residual damages still affect the lower parts of the city and are added to *City Costs*, along with the operating costs of the closure.

When MoSE is activated, the closure of these gates temporarily blocks the access to the lagoon from the sea and vice versa, causing a reduction of vessel calls at the Port of Venice and resulting in loss of revenues for the port's economic actors (e.g. port authority, agents, and workers).

For the port section, we also considered a potential negative *memory effect* stemming from the experience of encountering closed gates. Specifically, we assumed that (i) a fraction of the vessels negatively affected by a closure would avoid docking at the Port of Venice in the future, opting instead for nearby ports such as Trieste or Ravenna, and (ii) a fraction of the vessels negatively affected by a closure would only resume docking at the Port of Venice after 1 year (the parameter used in this routine is based on an unpublished report commissioned and kindly provided by the Port Authority). In our model, the costs faced by the port are accumulated in the stock variable *Port Costs*.

Navigation locks are not included in the current version of the model because, as stated above, they are not yet operational, and therefore, no information on their functioning is available. Furthermore, their effectiveness has been questioned by some authors (Tomasicchio et al. 2022; Vantorre et al. 2017), making their impact on future vessel traffic uncertain. Should the locks become effectively activated, the current version of our model might overestimate the actual damage to the port, even if delays in operations should still be expected. To account for the different timing of benefits and costs occurrence, we computed the net present value (NPV) of the flow of net benefits, that is, the avoided damages to the city minus lost revenues for the port for each closure, accruing over the period considered. The choice of the discount rate for the net benefits is crucial because, as is well known, the higher the rate, the less weight is given to long-term payoffs. This bias may affect the appraisal of projects that incur short-term costs and only yield benefits in the long term, which is a common problem for investments addressing the impacts of climate change.

In line with previous literature (Vousdoukas et al. 2020), we use the social discount rate. This is because, as a standard for projects of social value, the social discount rate allows considering the long-term opportunity cost of the funds spent on a given project from the perspective of the whole society, including future generations. The rates used in our calculations are taken from the European Economic Appraisal Vademecum 2021–2027 (EC 2021, 2015), which, following the conventional Ramsey discounting rule (Ramsey 1928), suggests 3% for the EU member states as a whole and 0.8% for Italy.

The simulations

The MoSE management model was initially executed using a historical record of lagoon water level data. Specifically, the two daily maximum and minimum tide values from 1983 to 2021 at the monitoring station of *Venezia-Punta della Salute*. This data was retrieved from the Venice municipality's official website (https://www.comune.venezia.it/node/6214). Initial tests and an extensive calibration and sensitivity analysis were conducted using data from January 1983 to October 2020, that is, the period before the activation of the MoSE system. The validation of the model results was conducted by considering the extreme flood event of November 2019, as we could rely on the quantified damage estimates provided by the municipal administration.

The sensitivity analysis was performed using Monte Carlo methods to explore the model's sensitivity to variations of the model parameters (e.g. the MoSE closure threshold), or uncertainties (e.g. the accuracy of tide forecasts). The results highlight the crucial role of the closure thresholds in determining the cost-effectiveness, while other parameters exhibit output variability within moderate ranges. For more detailed information on the methods adopted, the modelling procedure, and the results of the sensitivity analyses, please refer to the supplementary material available online. It provides comprehensive documentation and further insights into model development.

Our model calculated damages from November 12 to 17, 2019, flood for approximately 93 M€ (see Fig. 3). This figure is consistent with the order of magnitude of the reported damages, extracted from data provided by the municipal administration and the local press, which amounted to 82 M€ for the urgent interventions and structural damages to commercial activities and private properties. The overestimation can be justified mainly by the peculiar feature of the events which appeared as a sequence of three "exceptional" levels (above 140 cm) and 3 "very high" levels (above 110 cm) within 3 days, treated by the model as separate events. Moreover, the model considers also damages to economic activities (tourism in particular), which are not considered by municipal compensations.

After validation of the model, we proceeded to carry out simulations about future scenarios incorporating relative sea-level rises consistent with Representative Concentration Pathways (RCP) 2.6 and 8.5.

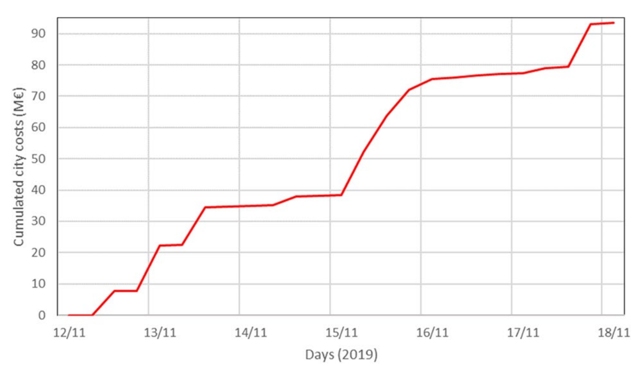

Fig. 3 Total cumulative costs of high tide events during the dramatic sequence of events between November 12 and 17 2019

Future SLR scenario simulations were conducted using two datasets. These datasets were generated by randomly extracting annual sets of observations (measurements of two high-tides and two low-tides per day) from records spanning the last 26 years. The annual sets were then recombined to create a 78-year sequence, generating a synthetic record from 2022 to 2100. We applied relative SLR (RSLR) trends in Venice, following the approach of Lionello et al. (2021), resulting in average estimates of 40 and 75 cm for RCP scenarios 2.6 and 8.5, respectively. These steps resulted in two time series, each representing four water levels per day for both the RCP 2.6 and the RCP 8.5 scenarios. These should be seen as deterministic estimates of plausible future water level records. The two time series can be considered as central tendencies of plausible future trends in RSLR, ranging between 30 and 110 cm by the end of the twenty-first century (Lionello et al. 2021).

Results

Costs and benefits of Modulo Sperimentale Elettromeccanico operation under sea-level rise scenarios

The first set of simulations was performed to calculate the avoided damages to the city and lost revenues to the port between 2023 and 2100, adopting the official closure threshold of 110 cm. Our findings show that the cumulative undiscounted avoided damages to the city amount to approximatively 112 B€ under the RCP 8.5 scenario and 25 B€ under the RPC 2.6 scenario. The corresponding undiscounted revenue losses for the port due to the closures are equal to 2.2 B€ and 1.3 B€, respectively (se Fig. 4). As stated above, taking into account the avoided damages for the smaller islands of the lagoon would increase the results by approximately 20%, thus further emphasising the substantial difference between the benefits for the city and the costs for the port.

Discounted at a 3%, the NPV is 17 B€ under RCP 8.5 scenario and 5 B€ under RCP 2.6 scenario. We note that the NPV under RCP 8.5 scenario is about three times higher than the NPV under RCP 2.6 scenario. This is because closures are relatively more frequent in the RCP 8.5 scenario, than in the RCP 2.6 scenario. Lowering the discount rate to 0.8% obviously yields higher NPV levels, specifically, 66 B€ and 16 B€, respectively. This is because, as expected, more weight is given to the long-term net benefits from MoSE. These benefits increase over time, as future floods become more and more dangerous for the city due to the SRL.

However, upon examining the outcomes of the simulation, serious doubts arise regarding the feasibility of the strategy based on a closure threshold set at 110 cm. The number of gate closures observed in the simulation raises concerns, as it far exceeds the original design expectations. The infrastructure was initially designed to accommodate a closure frequency ranging from 2 to 5 per year. However, during the 2 years of experimental operations, the frequency of closures was in the order of 15 to 20 per year. Such a high number of closures poses significant challenges for at least three key reasons: (i) the stress imposed on an infrastructure designed to handle a minimal number of closures in exceptionally high tides, (ii) the long-term effects on port attractiveness, which may lead to the collapse of commercial activities, and, very importantly, (iii) the adverse effects on the lagoon ecosystem and its water quality due to the reduced exchanges with the open sea. In this respect, it is worth highlighting that the city of Venice lacks an efficient sewage system, and wastewater produced by inhabitants and visitors is washed into the sea by the tide, largely untreated.

Despite the MoSE system having been in experimental operation since October 2020, as stated above, there remains a substantial lack of basic information about its operation and maintenance costs. As there is limited information available regarding MoSE operational and maintenance costs, we conducted a sensitivity analysis to explore the impact of its costs. According to our estimates, the theoretical benefits of the mobile gate system to protect the city of Venice far outweigh the investment costs of this defence infrastructure. Our findings hold true when considering operation costs per closure between € 30,000 and 300,000 and with

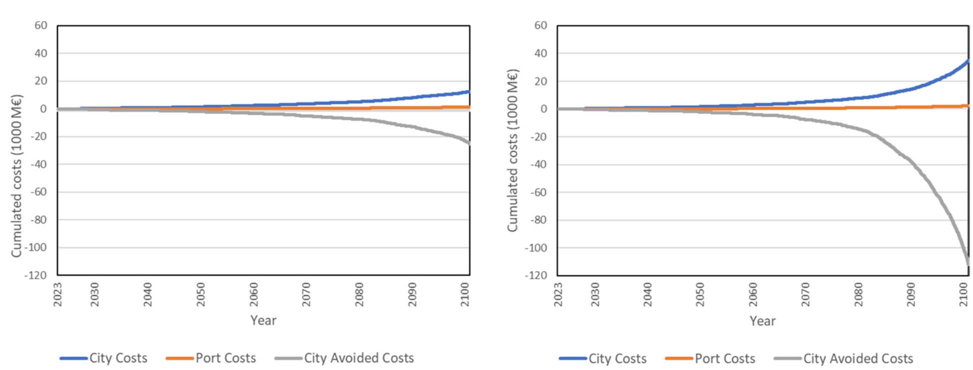

Fig. 4 Time series of cumulated residual and avoided costs for the city and costs (lost revenues) for the port, under estimated for RCP 2.6 (left) and RCP 8.5 (right) scenarios

annual maintenance costs up to 100 M€. The initial records concerning costs per closure during the current phase of experimental operation showed a decreasing trend from around € 300,000 to 210,000, while the annual resources made available for the coming year by the national government are 0.65 B€.

Taking into account our primary objective and considering the estimated final construction cost of approximately 5.9 B€ for the MoSE system, our simulations demonstrate that the economic benefits for the activities in the area protected by the mobile gates outweigh the investment costs by a significant margin. The trade-off with port activities exists, but the benefits for the city are greater. They are one order of magnitude higher than the implicit cost in terms of revenue losses for the port in the case of the RCP 8.5 scenario.

Management strategies and sustainability of the mobile gates

Upon examining the simulated data for the number of closures per year and per decade, we observe that the values are quite similar to those noted in the first 2 years of operation (17 events during the first year and 8 during the second with levels higher than 110 cm) up until the end of the 2050s. The number of closures ranges between 12 and 20 with a difference of around 20% between the two SLR scenarios. However, the two series diverge thereafter. In the 2060s, under the RCP 8.5 scenario, the number of closures remarkably increases and the average number of closures is 44.8. This represents a 47% higher average compared to the RCP 2.6 scenario. Eventually, during the last decade of the century, the average number of simulated closures reaches 624 and 210 per year under the RCP 8.5 and the RCP 2.6 scenarios, respectively.

The MoSE barriers remain closed in the presence of a series of very close consecutive high tide events that exceed the closure threshold, as has already occurred during the first 2 years of operation. Therefore, outcomes of the simulations were examined to estimate the number of likely prolonged closures under the simplifying assumption that the barriers are kept closed until the forecast is below the threshold. In the pessimistic climate RCP 8.5 scenario, using the currently adopted threshold set at 110 cm, we obtained an average annual number of prolonged closures increasing up to 44 during the last 10 years of the century, with a maximum duration of 4.5 days (18 time-steps). The impact of these prolonged closures on the overall economic performance is negligible, if we assume that the costs of MoSE operation and the port costs for prolonged closures are comparable to the sum of the costs of individual closures and that the benefits to the city are equal to the avoided damages corresponding to the highest water level occurring during the closure period. Nevertheless, the question of the technical limits of the mobile gates arises again, because at the time of their design prolonged closures were not considered.

Based on available observations, we estimate the average duration of closures to be approximately 6 h. The number of closures per year can thus be converted into a more effective and understandable indicator, i.e. the annual closure times reported in Fig. 5. In the worst climatic scenario and with closure level set at 110 cm, the values at the end of the century reach 5000 h, equivalent to 57% of the year. Once again, the results obtained show that well before the end of the century, the barriers could operate so frequently and for extended periods, that both their functionality and the impacts of closures on the lagoon would raise serious doubts about the viability of this solution in the long term.

The second objective of this study focuses on management strategies concerning the water level at which the barriers should be closed. They should consider the trade-offs between increased damages deriving from higher closure levels, which implies a larger part of the city left exposed to flooding, and higher costs and stress on the MoSE infrastructure from more frequent closures.

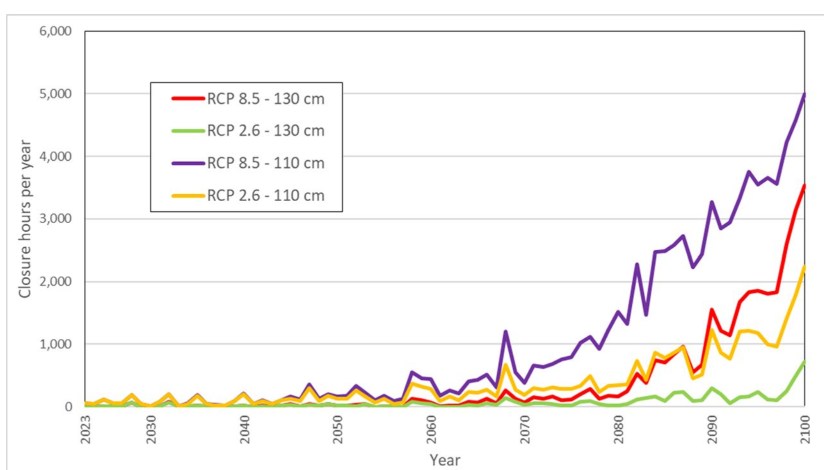

Fig. 5 The total closure times per year (hours) in the two climatic scenarios and the two closure thresholds considered in the simulations

A new set of simulations was performed assuming a closure threshold of 130 cm. In this case, less than four closures per year are estimated until 2050, and the frequency exceeds 20 per year under the RCP 2.6 scenario only in the last two decades of the century; under the RCP 8.5 scenario, this frequency is reached a decade earlier, but the average number of closures increases dramatically toward the end of the century, ramping up to 120 and 344 closures per year in the last two decades. Results of these simulations show that the cumulative undiscounted avoided damages to the city decrease to approximatively 68 B€ under the RCP 8.5 scenario and 10 B€ under the RPC 2.6 scenario. The corresponding undiscounted revenue losses for the port due to the closures are obviously lower than in the case of closure level set at 110 and are equal to 0.8 B€ and 0.3 B€.

An important factor affecting the operations is the uncertainty associated with the tide forecasts used to decide when to close the gates. During the first experimental period of MoSE operations, the closure threshold was set at 130 cm. The records show that the average actual water levels were 116.2 cm and in five cases, the observed level was even below 100 cm. We interpreted these data as the result of a precautionary criterion implemented to take into account the inevitable errors of the forecast (the closure procedure starts several hours before the peak, when the uncertainty due to evolving meteorological conditions is still in the order of ± 20 cm). If the same precautionary approach is adopted in the future, with the closure threshold now set at 110 cm, the number of closures could dramatically increase. Results for lower closure thresholds, i.e. 90 cm and 100 cm, are included in the sensitivity analysis reported in the supplementary materials available online. They show that these thresholds are unsustainable not only in the long term, but also in the medium and short term. For example, consider the RCP 8.5 scenario and a closure threshold set at 90 cm, the annual average number of closures in the period 2023–2100 ramps up to 352; in practice on average almost every day.

In summary, and with regard to the third objective of this study, our simulations show that it is very likely that the MoSE system cannot be operated at a closure threshold set at 110 cm until the end of the century as currently planned. The result would be an almost permanent separation of the lagoon from the sea, with dramatic consequences for the lagoon ecosystem, even assuming that the infrastructure could be used in a completely different and much more intensive way than planned, without substantial technical problems.

Discussion and conclusions

This paper contributes to filling knowledge gaps regarding the economic relevance of the defence infrastructure and its future viability. In particular, this study shows that the benefits of the MoSE system clearly outweigh the costs when the analysis is limited to its direct impact on the city economy. In terms of the trade-off between the protection of the city and the port activities, the estimated damages to the port caused by the operation of the MoSE system are an order of magnitude lower than the benefits to the city. Therefore, these damages could be considered as a negative side effect of protecting the city while waiting for the locks to become operational, and—in the longer term—for the construction of new offshore port infrastructure in the open sea, which is currently under discussion.

Although the economic performance is positive and robust, the main concern arising from our simulations relates to the expected increase in the number of closures due to RSLR, which could potentially lead to tipping points for sustainability of the MoSE. With the current closure threshold set at 110 cm, the number of closures rises significantly shortly after the mid-century mark, which could be unsustainable. The maximum acceptable number for technical and/or environmental reasons, however, remains unknown. For example, with a hypothetical maximum acceptable number of closures of 50 per year, which is more than ten times the planned number, the infrastructure might be overstressed after the 2060s under the RCP 8.5 scenario and about a decade later under the RCP 2.6 scenario. This leads to two main implications: (i) short- to medium-term strategies should be developed to reduce the number of closures and maintain the infrastructure, and (ii) medium- to long-term strategies should be explored to cope with sea levels beyond the operational capacity of MoSE.

For the short- to medium-term strategies, it becomes necessary to consider the possibility of adjusting the closure threshold to a level higher than 110 cm. In response, additional widespread investments would be needed to protect the lower parts of the city from floods well above 110 cm. This is the design level currently used for public works, especially for raising the street levels.

In terms of medium- to long-term strategies, it is worth noting that the design, decision-making, and construction of the MoSE system spanned about 50 years, with a projected lifespan of about a century. During the initial design phase of the infrastructure design in the 1980s, climate change and SLR were not primary considerations for decision-makers; it was only later that the system was identified as a measure to adapt the city of Venice to climate change. However, our analysis shows that the effectiveness of the system will diminish in the medium to long term, well before the end of the planned lifetime. Therefore, it appears that it is not too early to explore other solutions to protect the city beyond the MoSE system. Adaptation pathways (Haasnoot et al. 2021) should be explored taking into consideration a clever combination of a number of measures, including the elevating the city by pumping fluids (seawater) into deep aquifers, as proposed by Gambolati and Teatini (2014). Furthermore, given the prospect of a continuation and acceleration of RSLR, also the option of separating the lagoon from the sea by "polderisation" should be explored now, as it may become inevitable by or before the end of the century (Tagliapietra and Umgiesser 2023). If this proves to be the case, a long and costly series of investments will be needed well before the permanent closure of the lagoon outlets. Such investments would include addressing the sewage system, which is still inadequate in much of the city; the regulating or diverting the 27 small rivers that still drain into the lagoon; and relocating the city's port to an offshore site in the open sea.

The current version of the model is limited by the lack of relevant information, such as the cost of maintaining the barriers and the operational limits in terms of the maximum number of closures per year. Even more importantly, there is still lack of adequate quantitative evidences from ecological monitoring concerning the impacts of MoSE operations on the lagoon ecosystem, from the entry into operation of the locks (Tomasicchio et al. 2022), and from possible management strategies, such as the implementation of partial closures of the MoSE barriers (Mel 2021).

In terms of future opportunities by enhanced versions of the model, a significant contribution to the ongoing scientific and political debate surrounding MoSE operations would come from including in the evaluation of the impact on two relevant, but unfortunately competing needs: the conservation of the cultural heritage of the city and the preservation of water quality, the natural capital and ecosystem services of the lagoon. Their consideration is challenging since both assets and associated services have public good characteristics, and assigning them a monetary value could, as is well known, be contentious (Licciardi and Rana 2012; Mäler and Vincent 2005). When scientifically sound assessments become available, the modelling and valuation framework proposed in this paper can certainly be revised, enhanced, and employed to analyse the overall impact of the MoSE system and to explore potential adaptation pathways for safeguarding both the city and its lagoon.

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Author contribution CG designed the model and its application, and conducted modelling and analysis with MBi and BMF. MBr, VL, RP, and LDC analysed the economic damages for the city and port. UG analysed sea level rise and MoSE functioning. All authors contributed to data processing and discussion of results. CG and AG co-wrote the draft manuscript. All authors provided comments and edits to the draft manuscript.

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