The Value of Protecting Venice from the Acqua Alta Phenomenon under Different Local Sea Level Rises

Caporin, Massimiliano and Fontini, Fulvio

19 February 2014

The Value of Protecting Venice from the Acqua Alta Phenomenon under Different Local Sea Level Rises

Massimiliano Caporin[*] Fulvio Fontini[*] [†]

February 2014

Abstract

Venice (Italy) is built on several islands inside a lagoon. It undergoes a periodical flooding phenomenon, called "Acqua Alta" (AA). A system of mobile dams, called Mo.S.E., is currently under construction to protect it. When needed, several floodgates will be lifted to separate the lagoon from the Adriatic sea. AA, whose length and height has been increasing in recent years, is a random phenomenon, correlated with local sea level rise (LSLR). Several possible LSLRs can be assumed as consequences of different global warming scenarios. We investigate here the cost-benefit of Mo.S.E. under different possible LSLRs. First, we simulate the future patterns of AA for the next 50 years under alternative LSLRs. Then, we calculate the benefit of Mo.S.E., converting each avoided AA episode into an economic value (avoided cost). We show that the benefits are just at the level of the costs, when a low LSLR is assumed and increase with LSLR, provided that it does not reache a catastrophic (yet unpredictable) extreme level.

J.E.L. Classification code: Q54, D61, C22, C53.

---

[*] Department of Economics and Management, University of Padua, Italy.

[†] Corresponding Author. Address for correspondence: Fulvio Fontini, DSEA, University of Padua. Via del Santo 33, I-35123, Padua, Italy. E-mail: fulvio.fontini@unipd.it.

1 Introduction

The city of Venice is famous worldwide. It is built on several islands lying inside a lagoon and has unique historical and environmental features, that justify its inclusion among the UNESCO World Heritage Sites. However, its peculiar geographic location results in a periodic flooding phenomenon, known as "Acqua Alta" (AA), which threatens its preservation and interferes with people's everyday life. A system of mobile dams, called Mo.S.E. (an acronym that stands for Experimental Electromechanical Module, "Modulo Sperimentale Elettromeccanico" in Italian) is currently under construction. It is an innovative system based on a set of mobile barriers lying on the bottom of the lagoon's inlets. When needed, they are lifted to separate the lagoon from the Adriatic Sea and stabilize the height of the water inside it.

The Mo.S.E. system has been designed to protect Venice from AA for an extremely long times scale. During this time lag it will face the consequences that global warming will induce on the Venice lagoon and the AA phenomenon. Local sea level rise (LSLR) plays, inter alia, an important role for AA. Our data shows[1] that, in recent decades, both the height and frequency of AA episodes has increased. The increase in the episodes' frequency is, on average, equal to 0.7 episodes per year; the height of the yearly maxima has increased by 2.6 mm yr^{-1}. This is coupled with an estimated LSLR of 2.5 mm yr^{-1} [as a reference, compare it with the estimated Global SLR (assessed likelihood 90-100%) by IPCC (2013) of 3.2 mm yr^{-1}]. The higher a LSLR is, the higher and the more frequent flooding, and the higher the benefits of protecting Venice from the damages will be (but the interferences with harbour activities will be higher too). The benefits of Mo.S.E. can be contrasted with its costs. Mo.S.E. is a huge financial project. Its original budget, (1.6 billion euro), has been increasing manifold, the latest figure amounting to (roughly) 5.4 billion euro. The purpose of the present work is to evaluate the benefits of the Mo.S.E. net of the installation costs and the (expected) yearly operations and management costs. To do so, we first simulate the future pattern of AA for the next 50 years, replicating the observed time trend and simulating future AA under different possible scenarios for LSLR. We limit the analysis to 50 years since the economic evaluation is based on the actual technologies and knowledge, i.e., it does not take into account technological progress (for instance in real estate refurbishment or in the transportation sector) that can significantly alter the definition of the damage function. Then we convert these figures into an economic value by measuring the value of the avoided damage to Venice. Finally, we compare it with the reported investment costs and assess the Mo.S.E. cost-benefit. The paper is structured as follows. Section two explains the tide and AA and illustrates the methodology employed to run the simulations. Section three explains the relationship between AA, the LSLR and the damage to Venice. The results of the evaluation of the Mo.S.E. benefits are reported in section 4. Conclusions and references follow.

---

[1] Results are derived from simple linear regressions over a time trend of the hourly data, or daily maxima, from 1975 to 2009.

2 AA and tide simulation

AA depends on the tide in the Venetian lagoon, which is a partially random phenomenon. It can be defined as a tide above a given threshold, conventionally set at +80 cm above the Punta della Salute tidal datum. The latter is the level used by the Centro Maree - the public body in charge of monitoring AA - and beyond which the town starts to be flooded. Tides are generated by the interaction of two components: the astronomical tide and storm surge (Canestrelli et al., 2001). The former depends on the effect on sea level rise of a well-known set of deterministic parameters, the moon's influence and the season's changes being two of most relevant. The astronomical tide has a sinusoidal shape that can be calculated with very high precision. The astronomical tide, however, does not completely explain the observed sea level pattern in the lagoon. In fact, it is possible to identify (at least) three other main elements of the upper Adriatic Sea's climatology, that influence the behavior of the tide: winds, the barothropic pressure and the "seiches" (the oscillations of an almost closed basin, like the Adriatic Sea, after a perturbation). Together, these three components define storm surge. The interaction of storm surge and the astronomical tide determines the height of the sea level in the Venetian lagoon. Due to its nature, storm surge is a random phenomenon. Historical data show that it has had over the years an almost zero mean. The tide is thus a random variable given by the sum of a deterministic component and a stochastic component. As a result, it is possible to derive the random behavior of the tide by observing the stochastic pattern of the storm surge.

Within a given day, AA, if present, is associated with a maximum daily tide level above the threshold. Clearly, the duration of AA may vary from day to day, but this element does not affect the impact of AA on economic activities since the discriminatory element is represented by the occurrence of the phenomena (and not its length). Overall, using hourly data from the Centro Maree from 1941-2009 we measure the average duration of AA events and notice that AA's average duration is about three hours, with most events lasting between one and six hours.[2] Furthermore, AA took place (in almost all cases) once a day (despite the fact that the astronomic tide has two peaks within the day, one of them is generally much lower than the other). As a result and given the purposes of this paper, we focus on the daily maxima, and we evaluate the Mo.S.E. system using the daily time series of Venice lagoon sea-level maxima.

By construction, even the sequence of daily maxima is composed by the sum of two components, one being the astronomical tide and the second associated with storm surge. To evaluate the performance of the Mo.S.E. system, we need to simulate the evolution of daily maxima. To this end, we first specify a model for the daily maxima time series. Then we fit the model to data from January 1975 to December 2009, for a total of 12,784 days (sample size T). The period from 1941 to 1974 has been discarded since it includes more than 280 days with missing data. We preferred to focus on a complete set of years rather than replacing missing data with estimated values. Our aim is to provide long-range forecasts (or simulations) of the daily maxima. As a consequence, we chose to focus on a purely statistical approach, rather than an astronomical and meteorological approach, where the various components affecting the tide level are explicitly taken into

---

[2] Descriptive analyses of AA events duration are available upon request.

account. The model we consider assumes that the daily maxima time series is given as the sum of two components, mimicking the presence of two elements affecting the tide level. If we define as m_t the sequence of daily maxima, the series is decomposed as follows:

$$m_t = a_t + \sigma_t s_t, \tag{1}$$

where a_t is a deterministic component capturing the mean impact of the astronomical tide level on the daily maxima; σ_t is a deterministic component exploiting the effect of the astronomical tide in the dispersion of daily maxima; and finally, s_t is the stochastic component that we can associate with the storm surge. The two deterministic components, a_t and σ_t, have a similar structure, and are given by the combination of a linear component and a set of harmonics. The first term, a_t is set equal to:

$$a_t = \beta_0 + \beta_1 t + \sum_{j=1}^{Q} \left(\delta_j cos\left(\frac{2\pi t}{\omega_j}\right) + \gamma_j sin\left(\frac{2\pi t}{\omega_j}\right) \right), \tag{2}$$

where t denotes a linear trend, Q is the number of harmonics considered, ω_j, $j = 1, 2, \ldots Q$ are the frequencies of the harmonics, and β_0, β_1, δ_j and γ_j, $j = 1, 2, \ldots Q$ are parameters to be estimated. We stress that the sea rise level is associated with the value of parameter β_1. The harmonic frequencies are expressed in days and can be easily calibrated by looking at the periodogram of the daily maxima. Indeed, a similar approach has been used in other studies, for instance in the analysis of wind and temperature time series (Caporin and Pres, 2012, 2013) and in the finance literature (Andersen and Bollerslev, 1997).

Note that the frequencies are mostly associated with interpretable amplitudes of daily maxima oscillations such as the yearly and half-yearly components and the monthly and half-monthly lunar components.[3] In contrast, the deterministic dynamic of σ_t is specified after a log transformation

$$ln\left(\sigma_t^2\right) = \phi_0 + \sum_{j=1}^{P} \left(\rho_j cos\left(\frac{2\pi t}{\omega_j}\right) + \theta_j sin\left(\frac{2\pi t}{\omega_j}\right) \right), \tag{3}$$

where the number of harmonics and their frequencies can differ from those in equation (2), and the parameters to be estimated are ϕ_0, ρ_j and θ_j, $j = 1, 2, \ldots P$. Finally, the stochastic component, the storm surge, is modelled as an ARMA-EGARCH model:

$$A(L) s_t = B(L) \eta_t, \tag{4}$$

$$\eta_t = h_t^{0.5} z_t, \tag{5}$$

$$ln(h_t) = \varphi_0 + \varphi_1 ln(h_{t-1}) + \varphi_2 |z_{t-1}| + \varphi_3 z_{t-1}, \tag{6}$$

where L is the lag operator, $A(L) = \sum_{j=1}^{p} a_j L^j$ and $B(L) = \sum_{j=1}^{q} b_j L^j$ are the AR and MA polynomials, h_t is the conditional variance, z_t is the standardized innovation, and the parameters to be estimated are a_j,

---

[3] The latter can be associated with the anomalous, sidereal and synodic lunar months durations.

$j = 1, 2, \ldots p$, b_j, $j = 1, 2, \ldots q$, φ_0, φ_1, φ_2 and φ_3.[4]

The model parameters are estimated using a multi-step approach. First, we estimated the parameters in a_t by simple linear regression methods (with robust standard errors due to the presence of heteroskedasticity in the innovations) on the following equation:

$$m_t = \beta_0 + \beta_1 t + \sum_{j=1}^{Q} \left(\delta_j cos \left(\frac{2\pi t}{\omega_j} \right) + \gamma_j sin \left(\frac{2\pi t}{\omega_j} \right) \right) + \varepsilon_t. \tag{7}$$

Second, we estimate the parameters in σ_t again with least squares on the log-transformed residuals from the previous equation. In fact, $\hat{\varepsilon}_t = m_t - \hat{a}_t$ and $ln \left(\hat{\varepsilon}_t^2 \right) = ln \left(\sigma_t^2 \right) + ln \left(s_t^2 \right)$, therefore:

$$ln \left(\hat{\varepsilon}_t^2 \right) = \phi_0 + \sum_{j=1}^{P} \left(\rho_j cos \left(\frac{2\pi t}{\omega_j} \right) + \theta_j sin \left(\frac{2\pi t}{\omega_j} \right) \right) + \zeta_t. \tag{8}$$

Finally, the estimated s_t is given as $\hat{s}_t = \hat{\varepsilon}_t exp \left(-0.5 \hat{\sigma}_t^2 \right)$, and the ARMA-EGARCH parameters are recovered by maximum likelihood methods. The use of multi-stage estimation approaches is computationally convenient, but it clearly implies a loss of efficiency. Given the estimated parameters, the model can be easily used to generate long-range simulations for the evolution of the daily maxima time series. The simulation procedures we adopt are detailed in the following steps:

i Fix the simulation length M and, if needed, calibrate the mean trend, parameter β_1;

ii Generate the innovations for the ARMA-EGARCH model, namely the sequence of values for $zeta_{T+i}$, $i = 1, 2, \ldots M$ in equation 6; the innovations can be generated by sampling from a given density or, alternatively, by resampling from the model residuals; we adopt the latter approach to avoid making a distributional assumption;

iii Simulate the ARMA-EGARCH sequence s_{T+i}, $i = 1, 2, \ldots M$;

iv Add the deterministic components to the simulated stochastic evolution, obtaining m_{T+i}, $i = 1, 2, \ldots M$;

v To generate W different potential future evolutions of the daily maxima, iterate steps ii to iv.

The calibration of the mean trend parameter in step i allows replacing the estimated LSLR value with alternative figures. Such a substitution is crucial in deriving the evolution of AA events under different LSLR scenarios. In the following, we will make use of several values for β_1, each one associated with a specific LSLR hypothesis.

---

[4] We prefer the EGARCH model of Nelson (1991) to other GARCH specifications due to the absence of parameter constraints ensuring variance positivity and the contemporaneous presence of volatility asymmetry.

3 AA and the damage to Venice

The levels and frequencies of possible future AA episodes are converted into economic values by measuring the damage to the municipality of Venice due to AA. We follow the methodology proposed in Fontini et al. (2010), who considered two components for the damage function. The first one depends on the refurbishment of real estate damaged by flooding. No episode of AA has ever occurred during the months of July and August.[5] Therefore, the period of a year is considered, starting from the first of July until the 30th of June of the subsequent year. During this period, it is assumed that refurbishment and restoration take place only once (during the time of year with no AA) on the basis of the highest episode observed in the time span. The height of the tide determines the surface area of the town involved by AA and thus the number of buildings affected that need work. The municipality of Venice provides data of the portion of the town that is flooded for every 10 cm rise in the tide.[6] We follow the so-called "Frassetto" altimetry, which refers to the whole surface of the historical center that is flooded for every 10 cm increase of AA, not the the more recent "Insula" altimetry (see Boato et al. 2009) since the latter refers only to the public surfaces flooded, not to the whole surface.[7] A comparation of the two altimetries shows that, on average, 25% of the town surface that is flooded is public. For the remaining part, we assume that it is private and convert its surface area into the length of walls affected by floods using a (standard) one to one conversion. The cost of refurbishment (plastering) is applied to the length of walls affected by episodes of AA.[8] We consider constant 2013 prices and assume that 50% of buildings are of special (historical) interest and/or need aspecific care; for these, the costs of refurbishment are doubled. Table 1 reports the cumulative distribution function of the damage to real estate. Figures are in millions of euro. Note that it assumes a maximum beyond the +180 cm level since this is the level beyond which (almost) all of the town is flooded (such an extreme level has been historically observed just once, in the famous episode of the 4th of November, 1966).

[Tabel 1about here]

Table 1: Cumulative distribution function of damage to real estate due to AA.

The second component of the damage function depends on the frequencies of the AA episodes. Two levels of AA are relevant for this component. The first one is a level of AA that is high enough to hinder everyday activities, in particular the displacement of young and elderly people and tourism activities. Only episodes of AA above +120 cm are relevant for this component. We follow the methodology proposed in Fontini et al. (2010) that allows us to convert the number of Mo.S.E. activations above that threshold into values of

---

[5] See http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1754 [last access February 2014].

[6] See http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/2973 [last access February 2014].

[7] Notice, however, that in the "Frassetto" altimetry, some parts of the Venice, such as Giudecca, Murano, Burano, Torcello, Lido and other small islands are not included in the data. Therefore, we do not take into account these areas in our calculation.

[8] A fixed height of 1 m is assumed for plastering (with a ratio of 60% external and 40% internal walls), leading to a cost of 54 euro per linear meter.

lost tourism expenditures and replacement costs, for elderly people requiring daycare[9] and for babysitting (for school-age children who cannot attend school). The second relevant height is the activation level of the Mo.S.E. Consorzio Venezia Nova, the managing body that is in charge of building and operating the Mo.S.E., which has defined a tide level of +110 cm as the reference level for the tide inside the lagoon, once the Mo.S.E. has been activated. We assume that such a level will cap the height of water within the lagoon and the damage accruing from AA because of its height. On the other hand, every Mo.S.E. activation will have an impact on the Venice harbour activity. Indeed, Venice's main harbour is connected to the Adriatic Sea.[10] When the floodgates are closed, ships will first be hosted outside the lagoon and then allowed to enter through a lock gate. Ships already at the wharfs within the lagoon will have to wait until proper navigation conditions are restored. Mo.S.E. operation will thus entail costly delays in the harbour operations. Clearly, the more frequently the floodgates are kept closed, the higher the cost will be due to the interference with harbour activity, but the lower the damage to Venice due to AA will be. Vergano et al. (2010), considered two scenarios for the interference cost of the Mo.S.E. on harbour activity. The low-cost scenario assumes that lock gates will be actively operated and ship traffic flows will remain constant over time, while the high-cost one is based on an increase in ship traffic assumption and neglects the relief of delays due to lock gate functioning. We take the average of their figures[11] as the value of the yearly interference cost. The time series of the daily maxima shows that, on average, during the period considered in the study by Vergano et al. (2010), there has been a yearly average of 6.3 episodes of a tide maximum higher or equal to +110**.** This allows us to deduce an average interference cost per episode of Mo.S.E. closure that amounts to 0.168 million euro. Finally, in the evaluation exercise, we also take into account the yearly figures for O&M costs,[12] which amount to 13.3 million euro yr^{-1}.

AA forecasts depend, inter alia, on the LSLR. Because of the lack of data, we do not consider the possible interaction between global warming and the meteorological components of AA (storm surge) and take into account the possible LSLRs under different scenarios, simulating their impact only through the (annual) increase in the tide's trend. We consider five possible scenarios in which the LSLR ranges from the lowest level, which corresponds to the historical trend, to an extremely high level. In particular, we start with a scenario in which the sea level continues to rise at the same level as the historical trend (estimated on the basis of our data sample), namely 2.5 mm yr^{-1}. Clearly , such a scenario would exclude any increase in the LSLR due to global warming. There exist in the literature several possible scenarios that take the latter effect into account. We consider three further possible scenarios in which global warming plays a progressively increasing role. In particular, we first consider a low LSLR scenario, that assumes a constant yearly LSLR of 3.7 mm yr^{-1}. Such a level corresponds to the common starting value of the global mean SLR for the four

---

[9] Following Cellerino (1998), it is assumed that 10% of the population from 75 to 84 years old is confined at home and requires care during AA.

[10] Interferences with the activities of small tourist wharfs and other harbours located in Chioggia - mostly devoted to fishing - are not considered in our study because of lack of data.

[11] The updated figures are $653,601$ and $1,463,855$ euro, respectively.

[12] Updated from Fontini et al. (2010).

process-based projections (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) considered by IPCC (2013).[13] In those IPCC projections, such a level increases over time; thus, keeping it fixed corresponds to the adoption of an optimistic assumption about the LSLR. Second, we construct an "average IPCC" scenario, averaging the estimated rises extracted from the four process-based IPCC (2013) scenarios mentioned above and assuming a linear rise throughout the period. The derived figure equals 5.6 mm yr^{-1}. Interestingly enough, such a level coincides with the lower boundary for global SLR estimates, as reported by the National Research Council (2010). We also consider a pessimistic (high-rise) scenario assuming a yearly LSLR that derives from the IPCC scenario that delivers the highest projections for the global mean SLR, namely, the RCP8.5. It amounts to 7.4 mm yr^{-1}. Finally, we consider a worst-case scenario that corresponds to the highest forecast in the literature[14] from semi-empirical models (Nicholls et al., 2011), namely, two meter over the whole century. Such a figure, which also coincides with the upper bound of the forecast considered in the National Research Council report (2010), yields a (constant) yearly LSLR of 20 mm yr^{-1}. Table 2 summarises the five scenarios considered.

[Table 2 about here]

Table 2. Assumptions on LSLR for each scenario.

The five scenarios determine a different impact of LSLR on the AA. We conducted 10,000 simulations for each scenario. Figure 1 reports the yearly average expected number of Mo.S.E. activations for each scenario, a figure that is relevant for the second component of the damage to Venice due to AA. The left panel (Figure 1a) reports scenarios form S1 to S4, while the worst-case scenario S5 is reported in the right panel (Figure 1b). Figure 2 plots the expected average of AA events above 180 cm in each scenario, a figure that affects the first component of the damage function.[15]

[Figure 1a about here] [Figure 1b about here]

Figure 1: Expected number of Mo.S.E. activations in S1, S2, S3, S4 (left panel) and S5 (right panel) scenarios

[Figure 2 about here]

Figure 2: Expected number of AA events above +180 cm in S1, S2, S3, S4 and S5 scenarios.

---

[13] See IPCC, 2013, p. 1180.

[14] We do not consider higher SLR for several reasons. First, even if a higher rise can be obtained assuming the occurrence of catastrophic events such as the collapse of marine-based sectors of the Antarctic ice sheet, there is no consensus in the literature on the likelihood of those events. Moreover, a sea-level rise of several meters would have such a devastating impact both globally and locally that a punctual evaluation of the cost and benefit of a specific project (such as Mo.S.E.) would not have much meaning. Finally, the very functioning of Mo.S.E. is not assured for extreme SLR. Indeed, the Mo.S.E. is designed to work for tides up to three meters. The highest observed AA so far has been equal to 194 cm. Therefore, from a theoretical point of view, the Mo.S.E. can work for a LSLR just up to (roughly) one meter.

[15] The averages in Figure 1 are computed across the simulations for each year. In contrast, the averages in Figure 2 are derived across simulations and years.

We note that the higher the expected LSLR, the more frequent the Mo.S.E. activations will be in each year and the higher the episodes of extreme high AA will be. In particular, we can see that the frequency of Mo.S.E. activation rises exponentially for scenarios from S1 to S4; in scenario S5, it reaches a frequency so high that Mo.S.E. will (almost always) remain closed throughout the whole year in the last decade. Obviously, such a result depends on the extremely high level of LSLR assumed in the worst-case scenario. As for the frequency of the highest tide throughout period, we can see that, even in the most conservative S1 scenario, there will be two episodes of a tide above 180 cm in 50 years. Even if such an AA is, at present, considered an exceptionally extreme event, it is not implausible given that it has been observed once in the last 50 years and because of the continuing rise of the sea level. Clearly, such a frequency increases the higher the LSLR is, reaching an overwhelming figure of 25 episodes of AA above 180 cm in 50 years. Impressive as it might be, such a figure is not implausible, taking into account that, in the S5 scenario, there will be a one-meter rise of the sea level at the end of the period, which would imply that there would be several episodes of extremely high AA per year in the last decade.

4 The evaluation of Mo.S.E. benefits

The difference between the damages that would occur without Mo.S.E. and those that can be experienced once the Mo.S.E. is operated provides an economic measure of Mo.S.E. benefits. For each simulation of the tide level in a 50-year horizon, we evaluate the costs associated with AA episodes both with and without the Mo.S.E. To obtain comparable monetary figures, the costs are discounted at a 2% rate. Figure 3 plots the evaluation of the damages with and without Mo.S.E. for the S3 (average) scenario. The graph describes the median, the first and the third quartile and the min and the max of the simulations for the cumulated values of the first 5, 10, 25 and 50 years, with and without Mo.S.E. The dashed lines identify the Mo.S.E. total costs. All figures are in billion of euro, at constant 2013 prices.

[Figure 3 about here]

Figure 3. Damages to Venice in the S3 scenario with and without Mo.S.E. in 5, 10, 25 and 50 years.

Note that the damage increases over time as LSLR increase. Mo.S.E. functioning reduces the volatility of the estimates, since it caps the height of AA. Thus, the remaining volatility depends only on the expected numbers of its activation. We point out that, without Mo.S.E., there is an expected overall level of damages to Venice that amounts to 8.27 billion euro in 50 years. Mo.S.E. reduces it to 2.25 billion euro, thus determining an expected benefit, i.e., avoided damages, above 6 billion euro. Such a figure is above the reported costs, that amount to 5.4 billion euro. Therefore, we can expect a net positive value for Mo.S.E. in 50 years. Clearly, the value of the benefits depend on the different LSLRs assumed. Figure 4 summarises the benefits to Venice from Mo.S.E. in the S1, S2, S3, S4 and S5 scenarios. The figures (median values) are reported in

Table 3.[16]

[Figure 4 about here]

Figure 4. Mo.S.E. benefits to Venice in the S1, S2, S3, S4 and S5 scenarios in 5, 10, 25 and 50 years.

[Table 3 about here]

Damages with and without Mo.S.E. in the S1, S2, S3, S4 and S5 scenarios, in 5, 10, 25 and 50 years.

We can see that damage increases over time as expected, both without and with Mo.S.E. Its functioning reduces the damages. As a result, positive benefits accrue from the use of Mo.S.E. in each scenario. The value of the benefits increases with the LSLR for the S1, S2, S3 and S4 scenarios. The median figure ranges from 5.3 billions to 6 billion. Taking into account that the reported costs are 5.4 billions of euro, we observe a positive net benefit from Mo.S.E. under scenarios S2, S3 and S4. The benefits increase with the higher LSLRs assumed in each scenario, with a slightly negative figure for the baseline (no global warming) scenario S1. Looking at the figures of the first quartile and the maximum, we note however, that in S1, (almost) half of the simulations report a net benefit higher than the cost. Therefore, even in S1, we can assess a non-negative cost-benefit analysis for Mo.S.E. The figure of the extreme S5 scenario appears contradictory at a first glance, since the median estimate of benefit from Mo.S.E. is lower than the values for the other scenarios. This can be understood looking at the values of damage reported in Table 3. Note that the damage without Mo.S.E. in S5, even if it is higher than damage in S2 and S3, is not too high and are even comparable to the damage in S4 for the first 25 years of simulations. However, damage both with and without Mo.S.E. explodes in the second half of the considered period for the S5 scenario compared to the damage under the other scanraios. This determines the reduced values of benefits compared to the other scenarios. The explanation depends on the frequency of Mo.S.E. activations under the S5 scenario compared with activations in the other scenarios (see Figure 1a and Figure 1b), which determines continuous interference with harbour activity. However, we point out that a precise estimate of AA consequences in the S5 scenario cannot be considered as reliable as the estimates under the other scenarios, since S5 assumes a LSLR that is at the border of levels that are (supposed to be) compatible with Mo.S.E. operation[17] (and, on the other hand, even the probability of a SLR higher than the one reported in the RCP8.5 - our S4 scenario - cannot be reliably evaluated accrding to IPCC, 2013).

5 Conclusions

In this paper, we have provided an estimate of the value of the Mo.S.E system, i.e., the system of mobile dams that has been designed to protect Venice from the periodic flooding phenomenon of AA. We first

---

[16] Descriptive statistics for the 10,000 simulations per scenario are available from the authors upon request.

[17] See footnote 6 above.

calculated such a value estimating the possible future trend of AA under different possible LSLRs, and then we contrasted it with the reported investment and O&M costs. Our calculations provide a lower boundary to the value of protecting Venice for several reasons. First, because the data on floods and on economic activities, which are needed to calculate the economic impact of the floods, do not include all the boroughs of Venice and the other municipalities that lie on the Venetian lagoon (which are affected by AA) but only the central (historical) part of the town of Venice. Furthermore, the economic impact does not take into account all possible damages, for instance by excluding the impact of AA on shops and warehouse inventories, due to lack of data. The simulations of AA do not include the possible interaction between LSLR and storm surge, which could reinforce the frequency and height of AA. Finally, indirect costs (such as externalities), risk attitudes (which affect the option values of the investment) and strategic reactions to LSLR are not taken into account. Nevertheless, we have shown that the estimated benefits, which are largely higher that the original planned cost of the investment, have been greatly eroded by the increase in the budget during its construction. However, there is still a positive net benefit, whose value depends crucially on the assumed LSLR. In particular, the benefits are higher than the costs the higher the assumed LSLR, provided that it is not too extreme. If, on the contrary, there were a limited or null LSLR, the benefits of protecting Venice from AA would be entirely overtaken by the investment and O&M costs. Similarly, in the case of a catastrophic one-meter LSLR in 50 years, both AA and Mo.S.E. would interfere with everyday activites so frequently that the Mo.S.E. benefits would not be balance with its costs. Our work points out the importance of correct budget planning for investments of such a large scale and highlights the negative economic impact of high LSLR and consequently the importance of a large-scale adaptation expenditure, such as the Mo.S.E. system, to minimize it. It also casts some doubt on its positive net value, should a catastrophic rise happen (whose likelihood, however, cannot be assessed at present).

5.1 Acknowledgements

We thank Alberto Tomasin for having made available the data set of Centro Maree and jointly with Georg Umgiesser for their help on the Acqua Alta phenomenon. Clearly, we are responsible for the contents of the article. F. F. acknowledges the research grant PRIN-MIUR 2010-11 “Climate changes in the Mediterranean area: evolutionary scenarios, mitigation policies and technological innovation”.

5.2 References

Andersen, T.G., and Bollerslev, T., 1997, Intraday periodicity and volatility persistence in financial markets, Journal of Empirical Finance 4, 115-158.

Boato, L., Canestrelli, P., Facchin, L. and Todaro, R. (2009). Venezia altimetria, Comune di Venezia, Istituzione centro previsioni e segnalazioni maree, in collaborazione con Insula spa. Available at: http:

http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1754 [last access: February 2014].

Canestrelli, P., Mandich, M., Pirazzoli, P.A. and Tomasin, A. (2001). Wind, Depression and Seiches: Tidal Perturbations in Venice (1951-2000), Centro previsioni e segnalazioni maree, Comune di Venezia. Available at http://93.62.201.235/maree/DOCUMENTI/Venti_depressioni_e_sesse.pdf [last access: February 2014].

Caporin, M., and Pres, J., 2012, modeling and forecasting wind speed intensity for weather risk management, Computational Statistics & Data Analysis, 56, 3459-3476.

Caporin, M., and Pres, J., 2013, Forecasting Temperature Indices Density with Time-Varying Long-Memory Models, Journal of Forecasting, 32, 339-352.

Cellerino, R. (1998). Venezia Atlantide: l'impatto economico delle acque alte, Franco Angeli, Milan.

Fontini, F., Umgiesser, G. and Vergano, L. (2010). The Role of Ambiguity in the Evaluation of the Net Benefits of the MO.S.E. System in the Venice Lagoon, Ecological Economics, 69, 1964–1972.

IPCC, (2013). Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifht Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Available at http://www.ipcc.ch/report/ar5/wg1/ [last access: February 2014].

IPCC, (2007). Climate Change 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html [last access: February 2014].

Vergano, L., Umgiesser, G. and Nunes, P. A.L.D. (2010). An economic assessment of the impacts of the MOSE barriers on Venice port activities, Transportation Research Part D, 15, 343–349.

National Research Council, (2010). Advancing the Science of Climate Change. Washington, DC: The National Academies Press.

Nelson, D. B. (1991). Conditional heteroskedasticity in asset returns: A new approach. Econometrica 59, 347–370

Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., de Gusmão, D., Hinkel, J. and Tol, R. S. J., (2011). Sea-level rise and its possible impacts given a 'beyond 4 degrees C world' in the twenty-first century. Philosophical Transactions of the Royal Society A, 369, 161–181.

height of AA	damage (million euro)
≤80	0
81-90	0.56
91-100	6.97
101-110	23.03
111-120	69.08
121-130	135.01
131-140	177.12
141-150	189.16
151-160	194.94
161-170	195.85
171-180	196.07
>180	196.33

Table 1. Cumulative distribution function of the damage to real estate from AA.

scenario	impact on AA	LSLR
S1	historical	2.4 mm yr^{-1}
S2	low	3.7 mm yr^{-1}
S3	medium	5.6 mm yr^{-1}
S4	high	7.4 mm yr^{-1}
S5	worst case	20 mm yr^{-1}

Table 2. Assumptions on LSLR for each scenario

Scenario S5

years	Damage without Mo.S..E. (A)	Damage with Mo.S..E. (B)	Mo.S.E. benefits (A-B)
5	716	205	511
10	1,576	443	1,133
25	4,817	2,154	2,664
50	16,746	12,252	4,494

Scenario S4

years	Damage without Mo.S..E. (A)	Damage with Mo.S..E. (B)	Mo.S.E. benefits (A-B)
5	649	197	452
10	1,363	396	967
25	3,848	1,043	2,806
50	8,783	2,738	6,046

Scenario S3

years	Damage without Mo.S..E. (A)	Damage with Mo.S..E. (B)	Mo.S.E. benefits (A-B)
5	640	196	444
10	1,328	393	935
25	3,674	999	2,675
50	8,276	2,255	6,020

Scenario S2

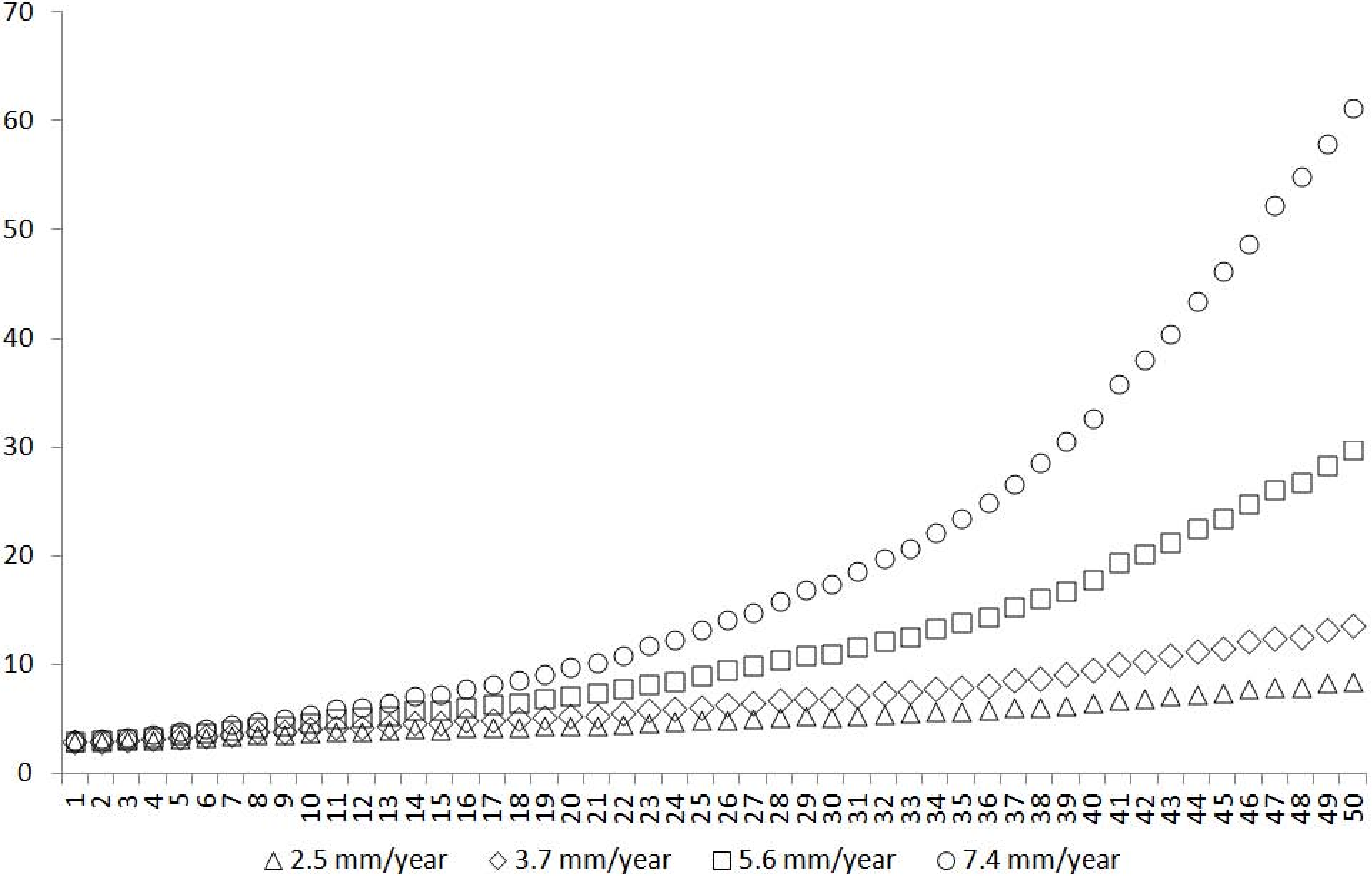
years	Damage without Mo.S..E. (A)	Damage with Mo.S..E. (B)	Mo.S.E. benefits (A-B)
5	622	195	427
10	1,292	388	904
25	3,475	964	2,512
50	7,640	1,976	5,664

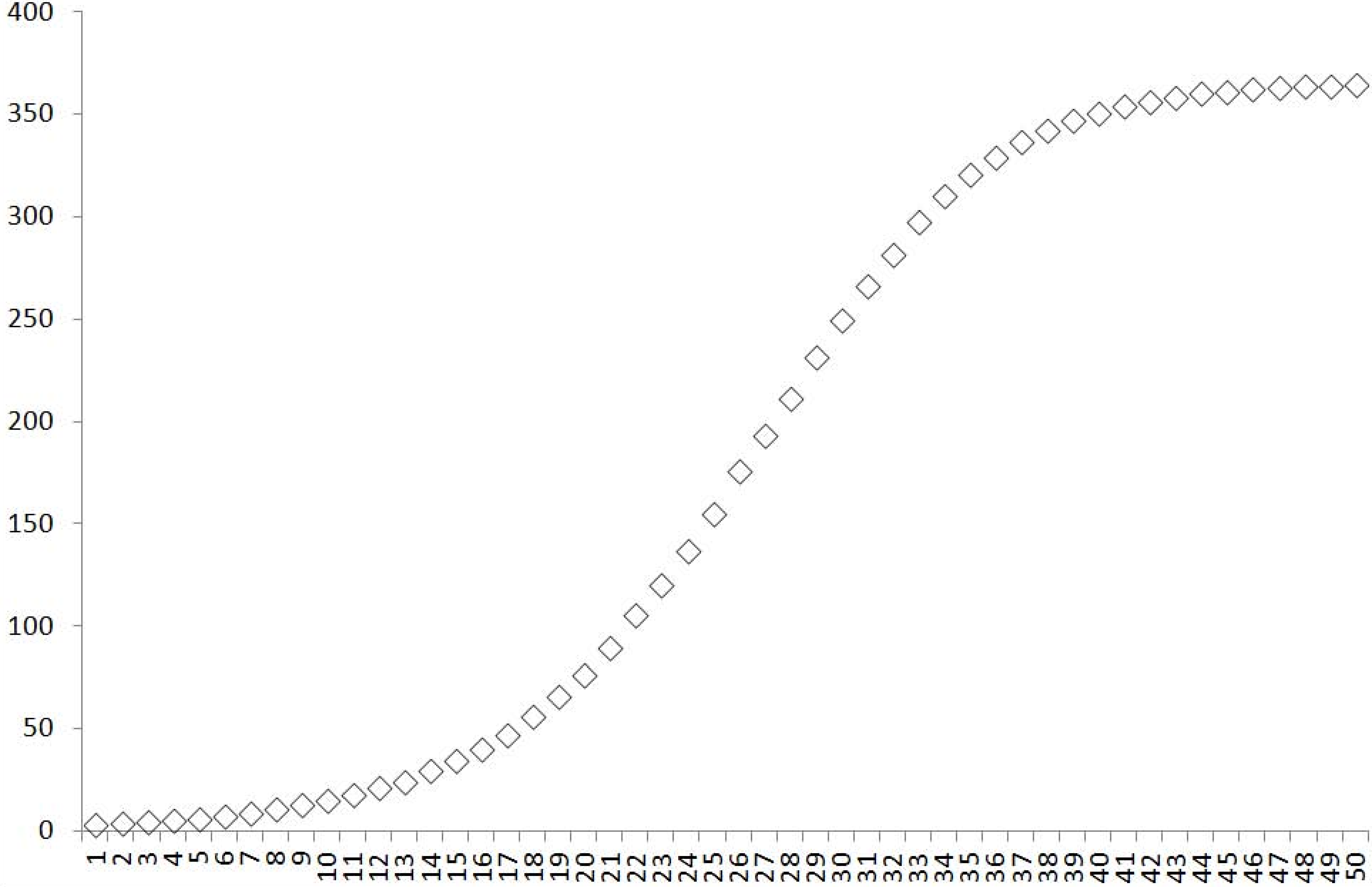
Scenario S1

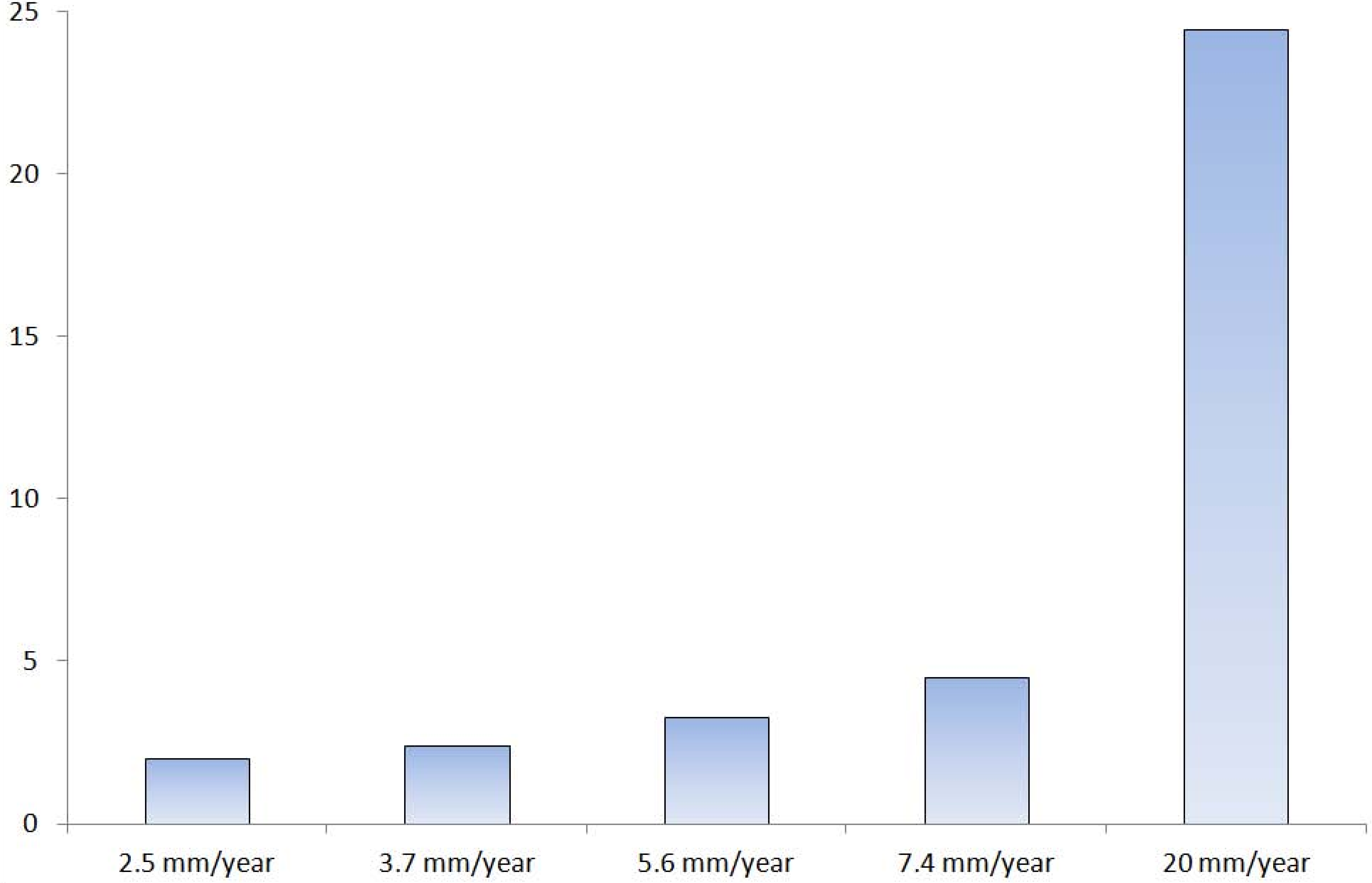
years	Damage without Mo.S..E. (A)	Damage with Mo.S..E. (B)	Mo.S.E. benefits (A-B)
5	613	195	419
10	1,269	386	883
25	3,349	946	2,403
50	7,197	1,871	5,326

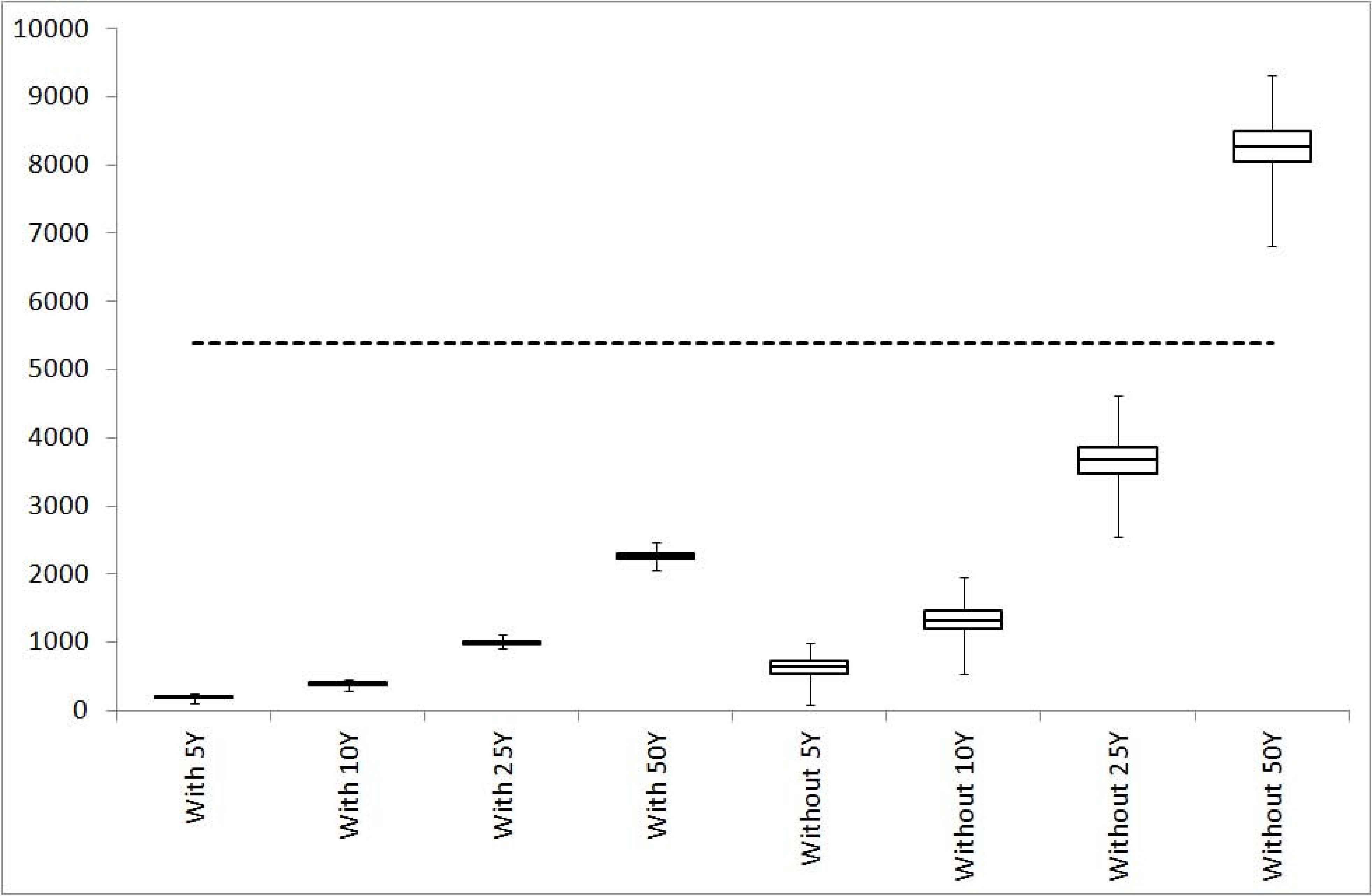
All figures are billion euro

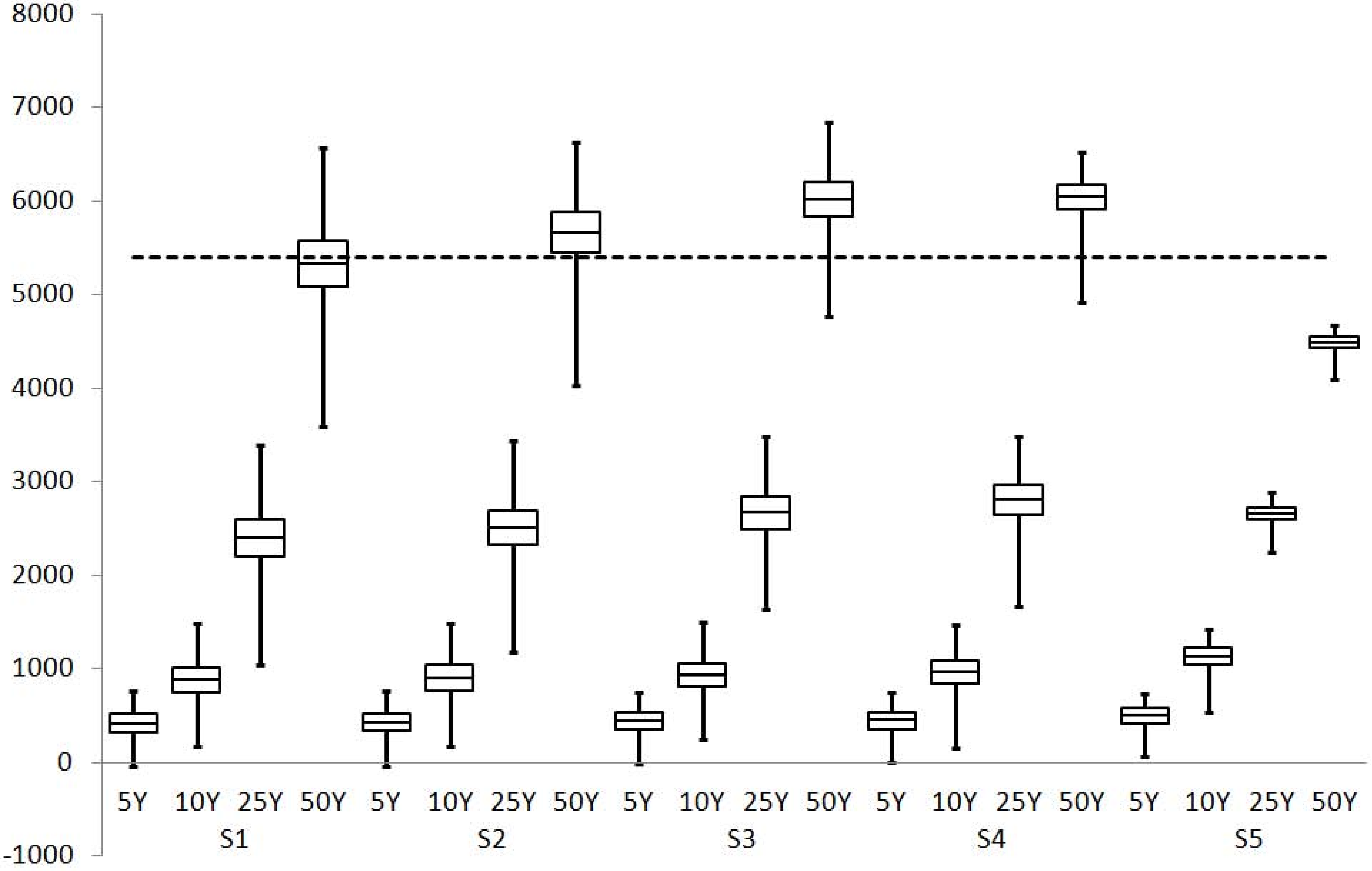
Table 3. Damage with and without Mo.S.E. in each scenario in 5, 10, 25 and 50 years.


0
10
20
30
40
50
60
70
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
△ 2.5 mm/year
◇ 3.7 mm/year
□ 5.6 mm/year
○ 7.4 mm/year


400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50


25
20
15
10
5
0
2.5 mm/year
3.7 mm/year
5.6 mm/year
7.4 mm/year
20 mm/year


10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
With 5Y
With 10Y
With 25Y
With 50Y
Without 5Y
Without 10Y
Without 25Y
Without 50Y


8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
5Y
10Y
25Y
50Y
5Y
10Y
25Y
50Y
5Y
10Y
25Y
50Y
5Y
10Y
25Y
50Y
5Y
10Y
25Y
50Y
S1
S2
S3
S4
S5