Aqua Alta: Venice - A City Built on Water

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Thursday, April 28, 2022

1 Introduction

Venice, a city of 126 islands separated by canals and joined by bridges and punts, has a unique relation to the surrounding Adriatic Sea. The Adriatic is both a defining feature of the city, yet increasingly threatens to engulf the city during what's known as "Acqua Alta," or "high waters." With a population of only 60,000 individuals, Venice stands as a monolith of Italian culture, dating to Ancient Roman times, with landmarks such as the Grand Canal, St. Mark's Square and Basilica, and the Doge's Palace, sites whose preservation requires constant maintenance and protection [Foot, 2020]. As over 80% of the historic city is situated below 2 meters above current day average sea level (SL) [of Venice, 2011], Acqua Alta frequently damages historical areas and is hazardous for both residents and the roughly 30 million tourists who visit annually. As these conditions are so disruptive, recent projects such as the MOSE barrier system have been installed to slow the deterioration of the city [Buckley, 2022]. While giving Venice some control over water levels, these projects have been plagued by high costs, slow construction times, as well as political corruption and embezzlement. Moraca and Imboden also point to lurking environmental concerns associated with changing the flow of water into and out of the Lagoon, citing low dissolved oxygen levels and the hindrance of natural marsh nourishment [Imboden, 2022, Moraca, 2022]. Our own sea level model, based on sea level fingerprinting, suggests that Venice will most likely face at least 0.21 meters of additional sea level rise (SLR) by 2100 from glacial melting alone, with subsidence and thermal expansion contributing up to an additional half meter [Yin, 2012]. By comparing Venice's geomorphology to it's flood history in the context of estimated SLR, we can model the risk Acqua Alta poses to the city's future. Addressing the ever increasing threat of flooding is a top priority for the city of Venice and Italy as a nation as they strive to protect their livelihoods and a worldwide cultural icon.

2 Constraining Venetian Sea Level Rise

2.1 Historical Analysis

To understand what 0.21 meters of SLR by 2100 means for Venice, we use historical data to model distributional changes of Acqua Alta, and factor in important local geological contexts such as subsidence rate. To derive SLR change by 2100 we used a fully elastic representation of the earth's response to melting ice caps, assuming fixed ocean-land boundaries and no rotation. We

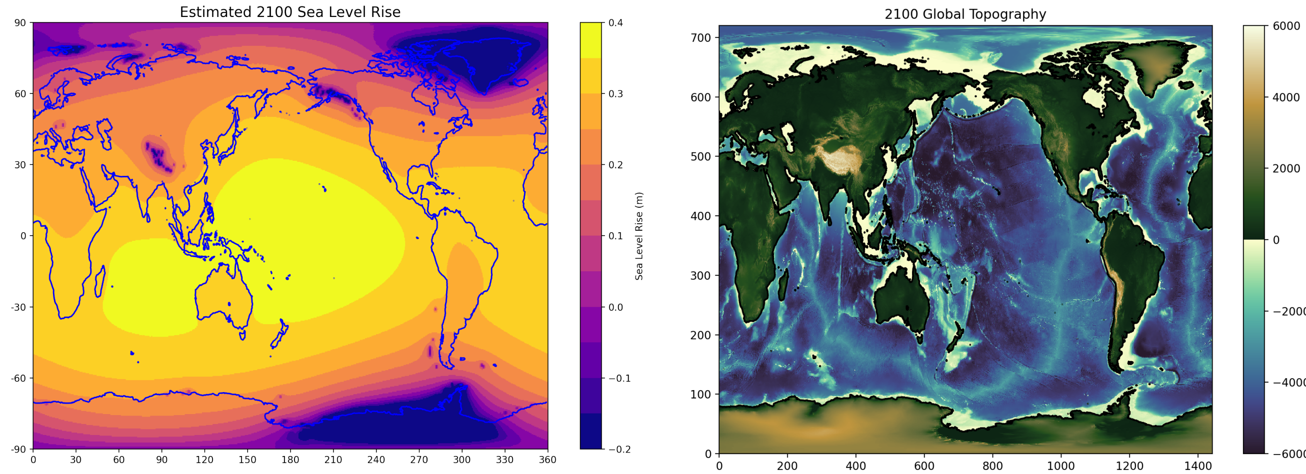

Figure 1: 2100 SLR estimates. **Left**: SLR Fingerprint from GrIS, WAIS, and Continental Glaciers mixed effects. **Right:** SLR superimposed on global topography.

combined the resultant sea level fingerprints from the Greenland Ice Sheet, the West Antarctic Ice sheet, and global glaciers proportional to their estimated melt rates, distributed evenly over the ice sheet footprint. For short time scales and distances far from the ice sheet, such as 100 years, these simplifying assumptions are reasonable because the Maxwell time is over an order of magnitude larger so viscous deformation will be comparatively small. Thus we capture a fairly accurate estimate of contributions of global SLR from ice sheet mass flux. The results of the sea level fingerprinting calculate combine an 11 cm contribution from both the West Antarctic Ice Sheet and continental glaciers and 8 cm from the Greenland Ice Sheet yields 21 cm. We plot the global distribution of SLR and resultant global topography in Figure 1.

2.2 Thermal Expansion and Subsidence Increase Venetian SLR Estimate

Assuming that glacial mass flux is the sole contributor to Venetian SLR would be a severe underestimate because this fails to account for thermal expansion and subsidence of the historical city itself. Yin et al. estimate will contribute an additional 0.1-0.4 m [Yin, 2012], and as thermal expansion does not significantly shift earth's gravity field, we can roughly assume this contributes to a uniform rise in global sea level (GSL). As SLR is modeled by the difference between ocean height and topography, we should also estimate topographical changes for Venice to further constrain SLR. Local estimates [Imboden, 2022] suggest that subsidence in Venice, due to artisan wells on the mainland which have been phased out, as well as soil compression under the city is on the order of 0.5-1 mm/yr. Over the next 80 years, we therefore estimate an additional 4-8 cm of SLR from subsidence. In total we estimate SLR to be between $0.21 + 0.1 + .04 = 0.35$ and $0.21 + 0.4 + 0.08 = 0.69$ meters.

2.3 Modeling and Prediction

To constrain Venice's SLR hazard, we use a historical empirical distribution of annual high tide events, a function estimating the flood portion via topography, and our previously derived estimates for SLR. While an overall rise in sea level will accelerate beachfront erosion and encroach

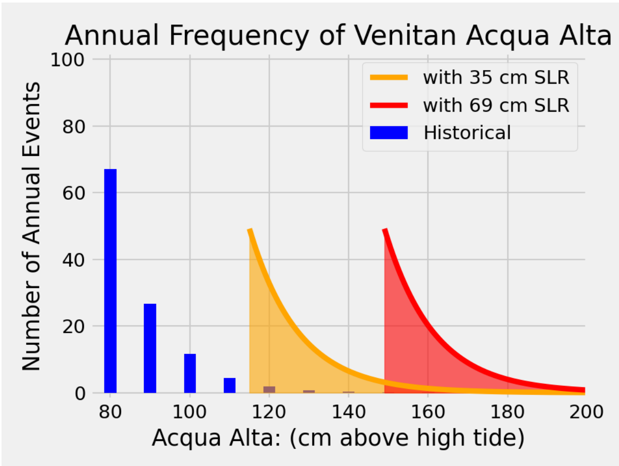

Figure 2: Historical Empirical distribution of Acqua Alta events in historical Venice, alongside with fitted and shifted predictions for SLR under low and high SLR predictions.

Scenario	Annual Extreme	Decadal Ext.
Historical	128	156
Low SLR (35 cm)	163	191
Mid SLR (50 cm)	178	200+
High SLR (69 cm)	197	200+

Table 1: Estimated highest average Acqua Alta event (in cm) historically and under low and high SLR scenarios.

on properties, Venice is used to strong tides and therefore an average increase in SLR is much less concerning than the threat from the highest Acqua Alta occurrences. Using an empirical frequency table of annual Acqua Alta events, we can capture the distribution of these extreme events historically and then use these to predict future high water hazard in Venice. Using a dataset from [Statistia, 2021], see supplementary Table 4 which collected observations over the past 100 years, recording the frequency of events every 10 centimeters, we observe that the distribution of Acqua Alta roughly follows a decaying exponential, which we fit to an exponential regression. Letting H be water height above average SL, F be the annual frequency, and ΔC_{SLR} be the estimated SLR, we fit our model to the historical and then can shift it to match estimated 2100 SLR.

$$\log(F) \sim \alpha H + \beta \implies \log(F) \sim \alpha(H - \Delta C_{SLR}) + \beta \tag{1}$$

To apply this model to the future we assume that other factors which influence Acqua Alta, such as the sirocco wind, remain relatively constant with a changing climate over the next 80 years. Shifting this model according to the estimated SLR yields a prediction for the distribution of annual extreme events in 2100 for Venice without human technological intervention (e.g. MOSE, see below). Using the estimates of 0.35 and 0.69m for lower and upper bound estimates for SLR by 2100 from section 2.1 we can estimate the distribution of Acqua Alta events. To understand what these distributions mean, we estimate the average most-severe annual and decadal Acqua Alta event and compare with historically damaging events. We summarize the results in Table 2.3, and highlight that even under the low SLR scenario, the annual extreme eclipses the historical decadal extreme. Furthermore, we find that 2 meters plus expected on a decadal frequency under mid and high SLR scenarios. For reference the highest surge to date was in 1996 at 194 cm. The second largest, on November 12, 2019 at 187 cm, had an estimated damage of 1.1 billion dollars according to ISPRA [ISPRA, 2020]. Given that the decadal worst case scenario of even the low SLR scenario is 191, we conclude that without large scale engineering Venice is doomed. Fortunately, the MOSE project, which came online 2 years ago is just that project.

3 MOSÉ: Parting the Adriatic

To protect Venice against damaging and costly high tide Acqua Alta events, Venice commissioned the Modulo Sperimentale Elettromeccanico (MOSE), a $7 billion dollar project designed to quickly seal the Venetian lagoon off from the rest of the Adriatic sea [Mills, 2021]. Unlike many other coastal cities, which are situated directly on the coast or in a bay, historical Venice sits within the Venetian Lagoon, shielded by a the island of Lido, and accessible via the narrow Treporti, Malamocco, and Chioggia channels. Thus a temporary system to block these channels was feasible. The MOSE project itself consists of 78 20-30m long float-able hinged fins, which can be raised or lowered within half an hour, and are activated when levels are predicted to exceed 110 cm [Buckley, 2022]. The barriers are capable of holding back up to 3 meters of high tide, making the biblical reference to Mosé, or in English, Moses, a fitting characterization.

3.1 MOSE Financial Criticism

The construction of MOSE was a protracted and politically controversial affair. While the project was initially concieved in 2003, construction did not begin until 2009 and was only completed at the end of 2019. The long build time was exacerbated when Venice's, now former, mayor was caught embezzling from the project [Buckley, 2022]. In addition to the $7 billion construction cost, the defense system requires $100 million to maintain annually, and over $300,000 for each time the fins need to be raised and lowered [Mills, 2021]. While receiving criticism for it's build price and maintainence costs, estimates of SLR from Table 2.3 suggests that by 2100, MOSE will be integral to preventing billion-dollar annual flooding events on the order of magnitude of the 2019 Acqua Alta flooding event.

Further financial debate around the MOSE project stems from concerns over disruptions to industry and vulnerability of different locales in the Venetian Lagoon. Industrial shipping, fishing, and cruise ships require near continual access into and out of the Lagoon. While access is still available through locks, delays and size limits hinder their ability to conduct business efficiently. Furthermore, under the current policy of raising the fins at 110 cm, an optimal level for historical Venice, damage occurs at other islands within the lagoon and lower levels, and those residents have been advocating for a lower activation threshold to protect their homes and businesses [Buckley, 2022].

3.2 Environmental Concerns: Marshes and Lagoon Anoxia

Alongside significant financial concerns, MOSE is already having a determinable effect on the Venetian Lagoon's ecosystem. The Lagoon has already lost upwards of 75% of its saltwater marsh to a combination of SLR and habitat destruction for industrial purposes. The remaining 25% are now also threatened by lack of sediment nourishment from flooding events, as MOSE decreases the tidal effect making the lagoon's currents during high water events wind dominated [Moraca, 2022]. While MOSE shouldn't be decommissioned over ecological concerns due to it's high efficacy, we should continue to research it's adverse affects on the surrounding environment and develop ways to mitigate those damages. For example, dumping or spraying sediments could help artificially nourish the marshes, helping to maintain the ecological services and habitat they provide.

While most recent MOSE applications have been short term, with typical applications ranging over a 3-4 hour high tide cycle [Imboden, 2022], future SLR will extend the time MOSE needs to be active for, potentially on the order of days if wind and tidal conditions remain strong. While lagoon ordinarily mixes with ocean water from the Adriatic, when MOSE is active the interchange stops which over time will result in anoxic conditions. These conditions stress and kill fish and other aquatic animals reliant on dissolved oxygen [Moraca, 2022]. Furthermore, the already brackish and polluted water of the Lagoon from human runoff [Momigliano, 2019] will further be concentrated, leading to more potent pollutants.

4 Conclusions

Venice's position in a lagoon at the top of the Adriatic Sea leaves it susceptible to dramatic and frequent Acqua Alta flooding, and additional environmental challenges such as delicate marshlands and high pollutant concentrations. Without human intervention the predicted 0.35-0.69 meters of sea level rise at the end of the century has the potential to dramatically increase the threat of Acqua Alta. Fitting historical data to a exponential, we are able to model future high water extremes, finding, for example, that even the best-case 0.35m SLR estimate will see a disaster equivalent to the $1.1 billion dollar 2019 flooding on a decadal time scale.

In the face of this large existential threat, the Venetian Lagoon itself allowed for a unique solution in the form of MOSE, which can completely isolate the Lagoon from the Adriatic at the push of a button. Without this system, our SLR model predicts the frequency of severe Acqua Alta to skyrocket, leaving large fractions of Venice underwater repeatedly over the course of the year. From Table 4 we found that historically 43% of the city is flooded annually, an annual rate which jumps to over 70% under the low SLR scenario and to 85% under the high scenario. Thankfully, MOSE is expected to be able to withstand up to 3 meters of SLR, a much-needed defence over the coming century. However, with this newfound power to open and close the Venetian Lagoon comes additional complex sociopolitical challenges and hazards. Navigating the wishes of city-dwellers, those living on smaller islands, and local ocean-going industry is complex, as each player wants different levels of protection from Acqua Alta and access to the Adriatic. Human and technical hazards also exist within the system. For example, in December 2020, a 145 cm surge hit Venice despite MOSE being fully operational because poor forecasting resulted in the system just not being switched on [Buckley, 2022]. One could also imagine this system being highly susceptible to technical failure as each of the 78 independent fins must activate simultaneously to seal the Lagoon. Given the 15 year build time for this system, a failure in 2100 could result in catastrophic flooding for the city.

Constraining SLR hazard is inherently a interdisciplinary and multi-faceted problem, requiring physical models to constrain absolute SLR, an understanding of delicate coastal geomorphology and ecology, and knowledge of human and political interests, objectives, and concerns. We should strive to engage with each aspect of coastal protection when designing an action plan, as while models are needed to highlight risks and estimate the magnitude of the challenge in front of us, an understanding of the environment, as well as sociopolitical interests and willpower are essential to make progress towards a productive mitigation strategy. For a beautiful city like Venice, such an approach is well worth the effort.

Sea Level (+cm)	% Venice Submerged
90	1.84
100	5.17
110	14.04
120	28.75
130	43.15
140	54.39
150	62.98
160	69.43
170	74.20
180	78.11
190	82.39
200	86.4

Table 2: Distribution of proportion of Venice that is underwater at different Acqua Alta levels [ISPRA, 2020]

Sea Level (+cm)	Annual Historical Frequency
80	67
90	26.7
100	11.7
110	4.5
120	1.8
130	0.71
140	0.32
150	0.09
160	0.04
170	0.02
180	0.02
190	0.02

Table 3: Historical Frequency of Acqua Alta by Sea level above average. [Statistia, 2021]

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