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The *Treatise on Waters* by Cornaro (1560) and a quantitative assessment of the historical sea surges "Acqua Alta" in Venice

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Abstract
In the sixteenth century, Cornaro wrote a *Treatise on Waters* with personal observations and conclusions regarding the Lagoon of Venice, e.g., the sea level rise over the centuries, the difference between normal tides for astronomical forces and storm surges driven by meteorological factors, and water exchanges between the Lagoon and the Sea. He witnessed the continuous rise of the sea level since the Middle Ages and listed some public works made to adapt to this challenge, i.e., raising city paving and floors, and rebuilding bridges that had become too low. Cornaro dealt with the mark left by the algae on walls that was kept as an official (zero) reference of sea level. Using this key to measure flooding depths, and knowing the relationship between the algae front and mean sea level, a revision of the historical floods (from 1240 to 1867) is made to assess precise depths. During the deepest floods, it was possible to reach San Marco square by gondola and float on the square. The draught of past gondola types has been another key to interpret flood depths. From 1200 to 1500, the most extreme flooding depths were higher than that of 1966, i.e., the highest in the instrumental record since 1871; from 1500 to 1799, they have been quite homogeneous, close to the value observed in 1966; in the nineteenth century, they returned to be higher than that in 1966. Over eight centuries, the deepest historical floods exceeded 7 times by 40 cm the 1966 extreme depth. The city should be prepared to face this risk.

Keywords Venice Lagoon · Sea level rise · Historical storm surges · Proxy data · Control of the lagoon inlets

1 Introduction

One of the major challenges affecting Venice is the occurrence of sea floods triggered by adverse meteorological conditions with low pressure over the western-central Mediterranean and Sirocco Wind blowing over the Adriatic Sea. The depth and frequency of these surges, locally called "*Acqua Alta*" (AA), are related to the sea level rise (SLR) and have increased, and will continue to increase, over time. The phenomenon has been intensively studied after the dramatic flood of 4 November 1966 (UNESCO

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1969). Today, the physical mechanism is well known, as well as the risks related to the projected SLR at global level (Trincardi et al. 2016; Cavaleri et al. 2019, 2020; Lionello et al. 2020; IPCC 2021; Zanchettin et al. 2021; Ferrarin et al.2022). All these studies are based on the regular tide gauge record that started in 1871.

A huge effort has been made to extend back in time our knowledge about SLR using documentary sources and proxies, e.g., the band of algae in paintings as a biological tracer (Camuffo and Sturaro 2003, 2004; Camuffo 2010) and the submersion of the sea stairs (Camuffo et al. 2017). The timescale was extended to AD 1350 with two conclusions: the mean sea level (MSL) was 130 ± 10 cm lower than nowadays; the SLR shows a long-term exponential growth (Camuffo 2021, 2022a).

The analysis of ancient documentary sources allowed reconstructing the AA from AD 782 to 1870 (Camuffo 1993; Enzi and Camuffo 1995; Camuffo et al. 2000). The sources report the year, a short mention of the catastrophic effects, at times an indication about the depth, e.g., up to the groin, the height of a man, or even a quantitative measurement in local foot. However, the depths remained obscure, lacking a precise reference level from which each depth was measured. So far, only the analysis of the frequency has been possible. In particular, the cumulative frequency of all AA has shown that the AA occurrence has increased more or less exponentially, but the fine distribution is affected by a number of turning points; the most relevant of them being around 1960, when the canal connecting the inlet of Malamocco to Porto Marghera was built (Camuffo and Sturaro 2004; Camuffo 2022b).

A book of the sixteenth century (Cornaro 1560), concerning the sea and lagoon waters, gives the key to recognize the reference zero from which the depth of flooding waters was measured, and this allows to interpret in a quantitative way the depth of the most extreme AA in the ancient sources (Enzi and Camuffo 1995). The severity of floods is reported in different ways, e.g., (i) damage caused to goods in warehouses or homes; (ii) depth of flooding waters measured in local units, starting from a so-far unknown reference; and (iii) mentioning amazing facts related to them, e.g., people riding in gondola over San Marco Square. It is clear that, when numerical thresholds are assessed, the events related to them may reach a quantitative value. For instance, is damage related to the flooding depth? Again, the greatest flooding depths have been reached when gondolas could float on San Marco Square. Over the centuries, the gondola changed size and shape. If we know the water depth needed by that gondolas to navigate, we can assess a threshold for the most extreme floods in the history.

The aim of this paper is to assess the depth of the most extreme AA of the pre-instrumental period and compare these historical depths with the level of 4 November 1966, that is popularly considered unprecedented, with waters peaking at 194 cm above local datum named “Salute 1897 zero reference.” However, in order to compare different depths in different periods, it is necessary to use the same unit of length, as well as the same reference zero. This is a problem not only for ancient measurements, but also for modern ones.

To reach our goal, the paper is organized by steps, i.e., introducing Cornaro, his treatise, and the Lagoon in the sixteenth century; measuring the sea level and flooding depths, after having defined the ancient and the modern units and their reference zero; revising the series of the most extreme AA; and commenting the findings on the light of the ancient and the modern Lagoon.

2 Cornaro and the Lagoon in the sixteenth century

2.1 The Lagoon

The Lagoon at the Cornaro's time is shown in a contemporary map by Sabbadino (1543 ca.), together with the today situation (Fig. 1a, b). In the antiquity, on the western side, some rivers entered the Lagoon. Over the centuries, these rivers have been diverted to avoid silting. On the eastern side, the Lagoon was separated from the Adriatic Sea by five islands that formed six inlets (i.e., Tre Porti, Liomaggiore, San Erasmo, Duo Castelli, Malamocco, and Chioggia) where seawater entered at rising tides and came out at falling tides. These inlets provided a natural exchange of water, including mud and sand, and the debate was to asses a balance between silt input and output, i.e., if the main problem were the turbid rivers (supported by Sabbadino) or the rough sea at storm surges (supported by Cornaro).

The Venetians based their activities on small boats for the Lagoon and large vessels for the sea. The inlets were considered the gate to Venice. Three inlets had deep waters; three had shallow waters. The former were crossed by large vessels; the latter by small boats with flat bottom. For foreign seamen, it was impossible to enter and cross the Lagoon because it was composed of small canals meandering through marshes (Fig. 1a) and the waterways were hidden under an apparently homogeneous water surface. The Venetians had learned to recognize the local depth from the small waves that were differently refracted in shallow and deep waters. Merchant ships could enter and reach Venice through the main inlets and deep canals. The main inlets were

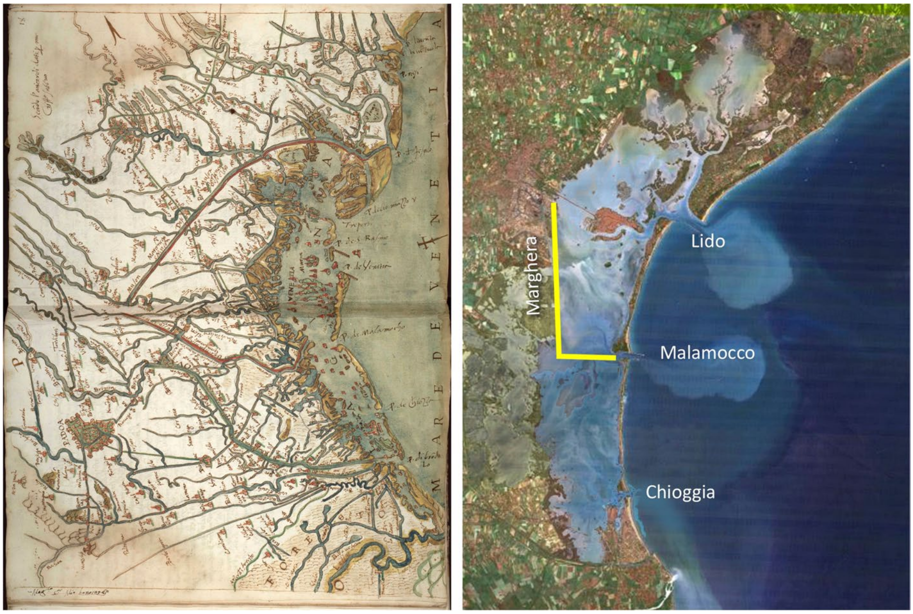

Fig. 1 Venice and its Lagoon. **a** Map by Sabbadino (1543 ca). The mainland is on the left side. The sea is on the right side, and five islands separate the Lagoon from the sea. **b** Satellite view of the Venice Lagoon with the three inlets Lido, Malamocco, and Chioggia (NASA Earth Observatory). The yellow line is the canal connecting Malamocco to Porto Marghera

organized with permanent civil and military structures, i.e., ports protected with defensive forts. For instance, the modern name “Lido” is a contraction of the ancient “li Duo Castelli” (literally: the two fortresses) from the two forts with guns, located on both sides of the inlet. After the protection works in 1744, when an extended dam called “Murazzi” was built, the inlets were reduced to three: Lido, Malamocco, and Chioggia.

2.2 Cornaro

Alvise Cornèr, in Italian Luigi Cornaro (born 1464, died 1566), lived in Padua, but was deeply involved in the life and problems of Venice where he was, or claimed to be, a nobleman. He was not a scientist; when he was a student, he dropped out of university because he considered that the lessons were empty words based on dated philosophic theories, disconnected from reality. He was a practical man, with several environmental and business interests.

He had relevant entrepreneurial skills in hydraulics and reclaimed the transformation of the Lagoon wetlands for farming (Ciriacono 2006). He obtained the permission to transform a part of the marshes into wheat fields and fishing ponds, at the same time, obtaining a healthy environment by reducing the foul reek, swarms of mosquitos, and winter fogs. He had excellent instinct, but sometimes, his position was dictated by personal interest. He was often in conflict with Cristoforo Sabbadino (Cornaro and Sabbadino 1551), a leading scientist officially appointed Foremost Engineer of Waters (responsible of the legislation and the hydraulic works in the Lagoon and the rivers of the Venice Republic). Probably for this conflict, he preferred to publish his *Treatise on Waters* in 1560, after Sabbadino died.

2.3 The Treatise on Waters

As specified in the “Foreword” of the *Treatise*, Cornaro was aged 85 and presented the content as a collection of the most relevant topics concerning the Lagoon and Sea waters, derived from his long experience. The *Treatise* includes his thoughts and shared knowledge presented as physical laws but limited to the statement, without demonstration. He explained that there was no need of demonstrations because it was enough to look around to be convinced. In other words, he listed and commented a series of empirical statements. Some thoughts represent the shared knowledge of the contemporary Venetians (e.g., tides), others his personal views in contrast with the common opinion (e.g., lagoon silting and river management).

The first thought (pages 4r–5r) concerns the marine currents and their deflection over the sailing routes kept by the Venetians inside the Lagoon, the Mediterranean Sea, and the northern Atlantic.

The next thought (pages 6v–9r) is a description of tides, tidal amplitudes, and storm surges. Regular astronomical tides occur twice a day. Tides related to the New or Full Moon (i.e., Spring tides) are wider, while those at the first and third Quarter (i.e., Neap tides) narrower. As opposed, in the occasion of storm surges, the sea may exceed the normal level by 1, 2, or even 3 feet (pages 6v–7r).

Another thought is the silting inside the Lagoon (pages 9r–20r), and the endless debate whether the main responsibility was the input of sediments from the rivers entering the Lagoon, or those from the sea during storms. Cornaro was especially concerned about the silting from the sea storms. The role of rivers was a key problem with several discussions (pages 20r–30r).

The conclusions (pages 30r–31v) summarize the main statements and underline the relevance of his thoughts, based on acute observation and long experience.

He also observed that the depth of the floods inside the Lagoon changed with the works made at the inlets, and that the smaller the inlets, the less the exchanges between the Sea and the Lagoon and the lower the maximum heights reached by the Lagoon waters during storms.

From this observation, he derived some practical applications. It may be possible to temporarily close the inlets when the water starts to exceed the normal level, i.e., the same basic idea of the mobile barriers that regulate the functioning of the modern MOSE to protect Venice from floods. He also suggested a number of interventions to reduce silting and improve the defense from floods, e.g., to deepen the inlet of Lido and close the other inlets; to divert the rivers that enter the Lagoon, creating new riverbeds and embankments to free the Padua and Treviso countryside from the risk of overflows; and to secure the port of Chioggia by building a wall and straightening the embankments.

A comment about the various thoughts would be too long and outside the allowed size of this paper. We will consider only the second thought, not to analyze and discuss it, but just to take advantage of his definition of the normal sea level and how the flooding depths were measured.

Formally, the *Treatise* is written in Italian, with a particular bombastic style derived from Latin and several repetitions to emphasize the content. Most words and ways of saying are idiomatic, typical of the sixteenth century, with several terms used only in Venice. Cornaro assumed that readers had a long navigation experience and were familiar with the marine environment that was normal for Venice citizens.

Depths are based on the Venice foot, as well as some other references that will be discussed later in the text. The units necessary to interpret the text are listed in Table 1.

The *Treatise* was printed in Padua, under Cornaro's direct control, by Gratioso Perchacino. The book is composed of 63 pages numbered on recto, i.e., the page number printed together with the front matter on the right-hand page. The verso (i.e., the left-hand page) is widow. Therefore, pages must be cited as for codices, i.e., r or v.

3 Measuring the sea level

3.1 Ancient and modern reference

3.1.1 The tidal cycle

Cornaro made a fundamental distinction between the regular tidal cycles related to the Moon, and the storm surges related to meteorological factors. He specified that "the sea usually rises 2 feet [i.e., 70 cm] in 6 hours and then falls for other 6 hours, making two cycles a day" (page 6r). He wrote that the tidal range was 2 feet (i.e., 70 cm). A key question is how Cornaro could measure it, and how 2 feet should be interpreted, i.e., an approximation to the nearest unit? or a reasonably precise value? How it could have been measured?

At that time, the tide gauge had not been invented yet, so it was impossible to take precise measurements. However, the Venetians benefitted of the sea stairs that every building had to reach the canal. All stairs were standardized: treads 1 foot depth, risers ½ foot height (Serlio 1600; Camuffo et al. 2017; Camuffo 2023). At high tides, the water reached the top

Table 1 Conversion from Venice units to the metric system

Venice unit	English translation	Definition	Metric system
piede	Venice foot	Primary unit	34.77 cm
oncia	Venice ounce (= inch)	1 ounce = $(^1/_{12})$ foot	2.90 cm
passo	Venice pace	1 pace = 5 feet	173.8 cm
gradino	Riser of a Venice stair	1 riser = ½ foot	17.38 cm
braccio (cubito)	Venice arm (cubit)	Primary unit	68.3 cm
bracherium	Groin, trouser crotch	Popular unit	75 cm
CM	Common mark or common marine level	Upper border of the algae belt, corresponding to the mean high tide plus small waves	42 cm above mean sea level
fondamenta	(Literally: foundations) Venetian name for street or quay level	Paving level of the City	> 100 cm above mean sea level

of the algae belt, and the stair appeared with all steps clear of algae. At average tide level, the stair appeared with two steps infested of algae; at low tides, four steps, and every Venetian knew that four risers make 2 feet. The resolution was a riser (17 cm), which was good considering that the noise generated by waves was 12 cm (Camuffo et al. 2017). Modern tide gauges can measure precise levels because their float is kept in a well of still water, connected to the sea through small openings that damp the wave motion. At Cornaro's time, the water surface was wavy and not precisely defined except for the front of the algae belt. If one sums the tide range (i.e., 60 cm) with the small waves (i.e., 12 cm), one obtains 72 cm, very close to 2 feet.

The tide of the sixteenth century may be compared with the present-day range, i.e., 60-cm median of the tidal cycles and 58.6-cm arithmetic mean. It might be surprising to find that the tidal range in the sixteenth century is similar to nowadays, i.e., only 15% less. The input is the tidal amplitude offshore that has not been changed, being determined by astronomical forces, while the Lagoon and its inlets have been affected by several important works in the past and recent times. The marine tide is filtered by the inlets and the morphology of the Lagoon (D'Alpaos 2010a; Matticchio et al. 2017).

Today, the water flow across the three inlets of Lido, Marghera, and Chioggia is much greater than in the sixteenth century. For instance, relying on the bathymetry of the Lagoon made by August Dénaix in 1810 (Magrini 1934), D'Alpaos (2010a) made a comparison between the values of maximum flow across the three inlets in 1810 and nowadays. The result is a major increase of flow across Malamocco (almost twice, i.e., 208%), followed by Lido (i.e., 140%), and a minor one in Chioggia (i.e., 127%). The explanation is that nowadays the cross sections of the three inlets are larger, but the number of inlets has been reduced from six (Fig. 1a) to three (Fig. 1b). The value given by Cornaro suggests a compensation between the two situations, i.e., six ancient shallower inlets versus three modern deeper inlets.

3.1.2 The sea level reference

A precious information concerns the definition of the sea level and the zero level from which the unusual tides or the flooding depths were measured, i.e., the "common mark" or "marine common level" (CM, see Fig. 2).

The text of the original quote is: "When the water returns many times to the maximum level, it leaves on the stones of the quays and the houses that are on the canals a dark mark at that height that is called 'common mark'" (i.e., CM, see Fig.2a, b). When water rises up to the usual front of the algae, without exceeding it, it is called "common", that is, usual. Returning many times to the same maximum level, the water leaves a dark mark at that height on the stones of the foundations and the houses on the canals. The common mark is formed when the sea is calm and without storms, and its water is quiet (page 6r). "When the stormy winds blow over the sea, the water is pushed from the sea to our shores which are located at the extreme end of this Gulf" (i.e., the northern Adriatic Sea, named Gulf of Venice). For this reason, the waters rise above the common mark by 1, 2, or 3 feet (i.e., 35, 70, or 104 cm) or more, according to the intensity of the storms. This elevation is called "above common" or above the sign of the common mark; therefore, it can be called and said above the ordinary, or extraordinary. Under these conditions, the sea is very rough, and the water is full of earth, raised from the bottom and from the shores" (page 6v).

This detailed description is important because the ancient chronicles reported that the seawater rose a certain amount X above the "normal," "ordinary," "usual," or "common"

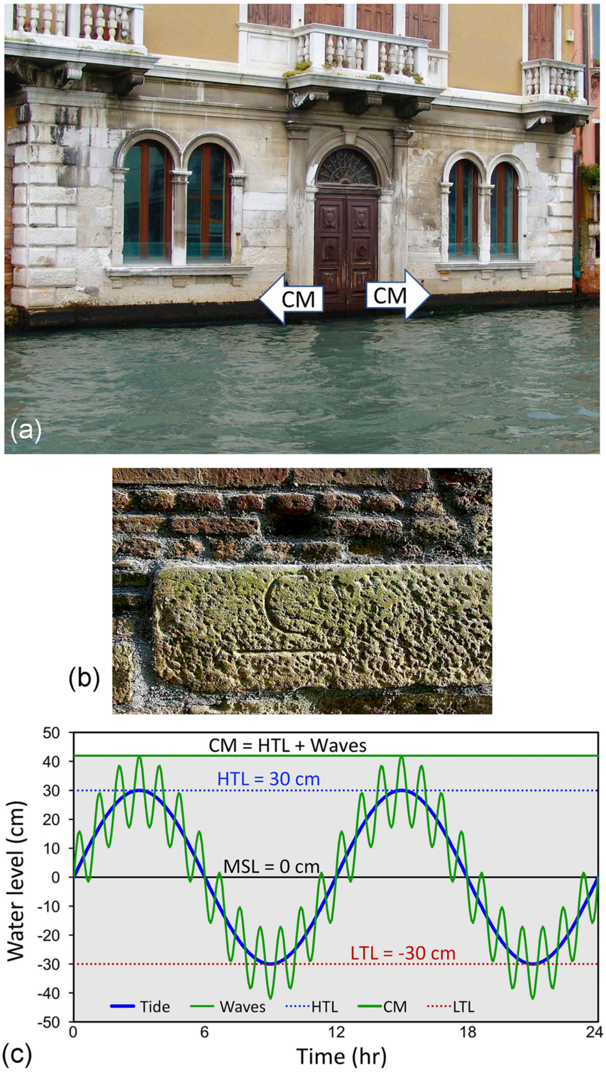

Fig. 2 **a** The dark-green belt formed by algae, named common mark or common marine level (CM) on the basement of all the buildings facing the canals. **b** A benchmark engraved C embedded in a canal embankment. The line below the C indicates the algae level at that time. (Photo © Daniele Resini, Insula spa, Venice, during cleaning and maintenance works). **c** CM is the front of the belt colonized by the algae, i.e., the level periodically reached on walls by the seawater at high tides (HTL), plus the contribution of small waves

level. However, in the scientific literature, this was interpreted as an obscure information because nobody knew what was the sea level at that time, not the perception that the ancient Venetians could have of it, or how they could assess a normal level before the invention of the tide gauge. It should be mentioned that a reference to CM was found in Temanza (1761), but there was no confirmation that the algae belt was considered as a reference in the early times too. This doubt is justified because accurate painters like Luca Carlevarijs (1663–1730) or Michele Marieschi (1710–1744) who lived in Venice before Temanza do not represent the algae belt on palaces. However, Cornaro informs us that CM was traditionally used in Venice, and this is very important because the algae front was related to the contemporary mean sea level (MSL).

The algae front is a basic benchmark, clearly visible everywhere (Fig. 2a), in all canals and along the coast. It was recognized to be apparently stable on the timescale of years, but slightly variable on the timescale of generations. In some cases, the ancient Venetians engraved it as CM, or simply C, on walls as an official reference of the sea level when the benchmark was made. The level was indicated with a line below the acronym (Fig. 2b).

Following Rusconi (1992), CM was considered to be the level reached by high tides, i.e., 30 cm above MSL. However, it has been later found (Camuffo et al. 2017) that the dark band of algae is determined by the front of wetting, i.e., the level periodically reached by seawater as a combination of the high tides and the superposition of the small local waves (Fig. 2c). In the past centuries, when the small waves were due to wind and row boats, CM was 42 cm above MSL, or 12 cm above the high tide level; nowadays, with motor boats, it is 5 cm higher (Camuffo et al. 2017).

It is clear that the ancient data can be compared with the modern ones after all depths have been homogenized. The ancient data were in feet measured from CM, while the modern data are in millimeters measured from another arbitrary reference level, taken as zero. Since the beginning of the instrumental record (i.e., 1871), the Authority in charge decided that the sea level in Venice, the Lagoon and the coast was measured by referring to the historic tide gauge of Punta della Salute. The reference was established on the basis of 25 years of tidal surveys, from 1885 to 1909, and the zero was established to refer to 1897, i.e., the central year of this period called "Salute 1897 zero reference" (Municipality of Venice 2022). The national altimetric network for monitoring ground vertical movements, the former Water Magistrate, and the Tide Office of the Municipality of Venice for tidal forecast and warning, all exclusively refer to this zero.

4 Sea level rise

Originally, the quay and street level in Venice was established at a safe height above CM to avoid the risk of being flooded. However, the need to upload and download food and goods from boats required that the quay level corresponded to the shoulders of a man standing on boat, and this is confirmed by the ancient paintings representing Venice (Camuffo et al. 2017; Camuffo 2022b). However, the sea level rise and the local land subsidence changed CM over time, as well as the level of San Marco Square, as discussed later.

Cornaro wrote that the contemporary CM level was 3 feet higher than three centuries before, and that the sea level rise had obliged to raise by 3 feet the city paving, including churches and ground floors in buildings, as well as to rebuild the bridges that had become too low for the passage of boats (Cornaro, pages 9v–10v). In the middle of the sixteenth century, the rate 1 foot/century was biased for the incorrect dating of some remains taken as a reference. Sabbadino (1543 ca) too was conditioned by the same bias and initially assumed it, but after further analyses, he arrived to the average of 11 ± 1.6 cm/century (Camuffo 2021) that is close to the value 13.50 ± 1.7 cm/century obtained with the reconstructed proxy series (Camuffo et al. 2017; Camuffo 2022a). However, although the rate assessment was uncertain, it is certain that Venice undertook urban works to adapt to the increased sea level.

Like every Venetian citizen, Cornaro knew that in the ancient times until the 1260s, people and horses traveled on streets and squares in bare ground, with undefined and uneven level. San Marco Square was a "brolo," i.e., a typical medieval combination of garden and orchards, where people could meet, walk, or organize open sky markets. "In the 14th year of dukedom of the Doge Renier Zen (i.e., AD 1260) this green area was paved with herringbone brick pattern" (Dandolo 1280 ca). The same is in other chronicles: "in 1262, the

Doge Zen built the clock on the Church of San Marco and paved the Square, as we can see today" (Anonymous 15th Century). "In the 1st year of the Doge Antonio Venier (i.e., AD 1392), the floor was raised and paved with bricks, but forming squares with strip borders in white Istria stone" (Savina 1412 ca.; Procuratori de Supra 14th century; Musatti 1881; Saccardo 1892). This old paving is visible in a painting dating 1496 by Gentile Bellini, representing the Procession in San Marco Square, now housed in the Gallerie dell'Accademia, Venice. In 1723, the Square was raised 1 foot and paved with square stones of gray trachyte decorated with white stone strips (Quadri 1830). In 1888–1890, the Square was raised and paved again with the same style (Dalle Piane 1992). The trachyte stone was appreciated for paving because it is a local igneous rock (composed mostly of alkali feldspar), resistant (Moh's Hardness Scale 6), and is not slippery even when some water lies on it. In 1885, in the occasion of some excavations made to consolidate the bell tower, the ancient herringbone brick floor was found 72 cm below the paving level (Boni 1885). The adaptation strategy was to raise the basic City level. However, this strategy had the limit that sea stairs were submerged; by raising the floors, the rooms were reduced in height, doors and windows had to be adapted, and bridges had to be abated and substituted with taller ones.

Cornaro (pages 9v–10v) correctly excluded that the observed rate of SLR inside the Lagoon could be attributed to the shrinkage of the Lagoon borders, and that its actual capacity was irrelevant because it was in communication with the open sea. He (wrongly) excluded any local land subsidence (page 10r) because he imagined that land was solid and resistant; the fact that land too may have vertical movements was discovered two centuries later (Pini 1793). Therefore, Cornaro was convinced that Venice was facing a real SLR and that this was the only cause.

5 Historical storm surges

The historical floods mentioned in the documentary sources have been presented and commented in Enzi and Camuffo (1995). As anticipated, Cornaro gave the key to transform in modern units the historical floods measured in feet above CM, as they were taken with a tide gauge. It is also possible to refer them to the average sea level of that current year. This section is focused to assess the flooding depth of the most exceptional surges occurred in the pre-instrumental period and remove from this list the minor ones.

5.1 Flooding depth and damage: are they related?

For several climate proxies, including river floods (Glaser et al. 2010; Blöschl et al. 2020), the intensity of the events is assessed in relation to their environmental or socio-economic impact, e.g., people or animals killed or damage to bridges, buildings, and agriculture. In this specific case, however, things are different. The case of AA implies an exceptional rise in water level without the (dynamic) pressure and the horizontal drag force exerted by the turbulent mass of water outflowing from rivers and accelerated by slopes. In AA, the mechanism is static and the damage is for soaking with salt water; on the other hand, in outflowing rivers, the mechanism is dynamic.

The documentary sources report several cases in which wells were contaminated by salt water that constituted a serious drawback. Venetian wells are not fed by underground water because it was impossible to reach the water table: "Venice lies in the water, but has no water" (Sanuto, 1496-1533). Therefore, the Venetians built cisterns, named "wells," to collect and filter rainwater, following a standard procedure (Scamozzi 1615). The cisterns (see

ESM1) were topped with stone paving to obtain a large catching surface, at normal street level, and people could freely walk on it. The paving acted as an enormous funnel and when the sea flooded the streets, the salt water entered the cisterns, making them bitter and unusable. This required emptying and washing the cistern and replacing the contaminated sand with new one transported by boat from the rivers. This was an enormous damage that even a modest AA at street level could cause.

For working efficiency, i.e., to unload merchandise from boats, or load them, it was convenient to keep warehouse and storage rooms at ground floor, near the quay, while the family prudently lived at the upper floors. To reduce the risk of damage, the quay and the floor level was kept elevated from the CM, but SLR and land subsidence worsened the situation. Therefore, any AA reaching the floor caused irreversible damage to merchandise which consisted of precious goods from the Orient (e.g., silk, wool, brocades, incense, spices, sacks of cereals, sea salt), so that the real damage depended heavily on whether the warehouses were full or empty, the quantity and quality of the goods in storage, and little on the reached depth.

Therefore, every modest AA with water slightly above the street level could cause enormous damages and the socio-economic impact is not representative of exceptional depths. Therefore, the events mentioning damages, but not supported by further information, have been removed from the list of the most extreme floods.

5.2 The flooding depth when gondolas could reach San Marco

A potentially useful index of extreme flooding depths is when boats reached San Marco Square. During the instrumental period, i.e., 1871–today, this happened only in 1966. However, this is not the first time in the history, as reported by ancient chronicles and the paintings by Vicenzo Chilone, Federico Moja, and Felix Ziem (Camuffo 2022b, 2023). In order to assess the related water depth, we should know the performances of this boat. The problem is that the modern gondola has different size and shape than in the historical period. Although the history of the gondola has been the object of several works (Pergolis and Pizzarello 1981; Gillette 1988; Marzo Magno 2008; Munerotto 2010; Penzo 2016), some crucial aspects remained obscure, namely, the origins and the transformation of the sixteenth century and when and why it happened.

A study has been recently made to clarify these aspects, and in addition to estimate the draught of the various gondola types (Camuffo 2023). Initially, from 1100 to 1509, the gondola was arched, light, and elegant (Fig. 3a). In 1509, the gondola was transformed in a military boat (Fig. 3b) to be used by Venetian commandos to fight in the rivers Po and Adige, during the war against Ferrara and the Allied of the Holy League of Cambrai. The gondola was bigger, reinforced with a rostrum on bow and another on stern to crash against the enemy boats. It was built symmetrically to go in either direction without having to turn, thus making maneuvering quicker and easier in confined spaces. This type survived until the second half of the seventeenth century. After, it was gradually transformed from military to civilian boat, propelled by a single rower or two, and the bow was differentiated from the stern. In the eighteenth century, the gondola became the famous romantic boat represented in all the Venetian paintings (Fig. 3c).

Over the centuries, the length was increased, but the hull width and height had only minor adjustments. The hull depth was 65 cm, of which 3/5 (i.e., 39 cm) submerged. At maximum load, with passengers and rower, the draught may reach 1.5 feet (52 cm). Under dynamic conditions, the rowing strokes, wind waves, or movements of passengers generate

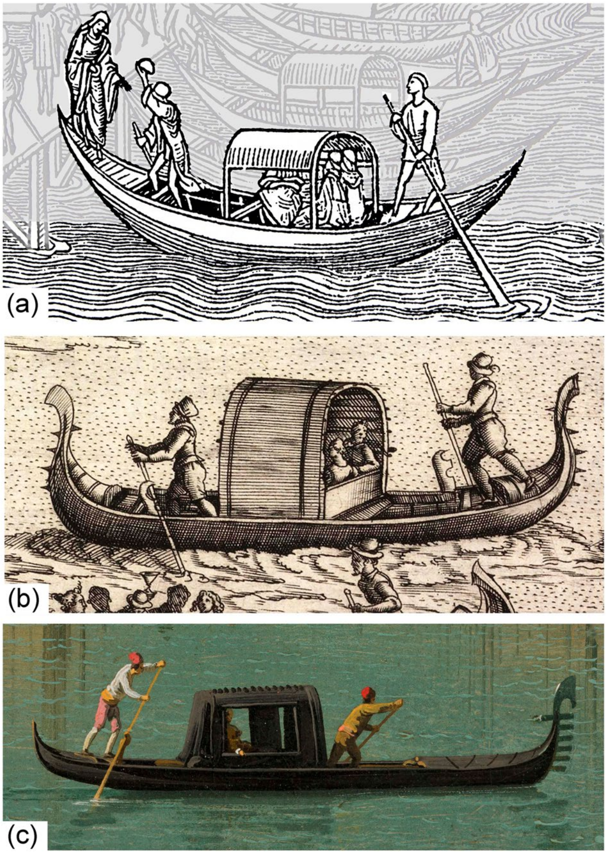

Fig. 3 The three main types of gondola. **a** An arched gondola of the sixteenth century (from Breydenbach 1486). **b** A symmetrical, military gondola of the sixteenth to seventeenth century, with a rostrum on both ends (from Franco (1610), by kind permission of Internet Culturale, Marciana National Library, Venice, license CC-BY-NC-SA3.0-IT). **c** A baroque gondola of the eighteenth century (Canaletto, 1725, detail of "The Grand Canal, seen from the Rialto Bridge", by kind permission of Paris Musées, Musée Cognacq-Jay, license CC0)

some pitch and roll that are not damped by the flat bottom. Therefore, when the gondola is moving, the hull and the pivoting oar require a water depth 60–70 cm for safe navigation in shallow waters.

In conclusion, when the ancient chronicles mentioned that gondolas could reach San Marco, the seawater had to reach the street level, plus 60–70 cm for navigating. The street level changed over the centuries for the combined effect of sea level rise and land subsidence. In the next sections, these have been computed as discussed in Camuffo et al. (2017).

6 Discussions

6.1 Revising the depth of the historical Acque Alte

The paper of Enzi and Camuffo (1995) is a basic collection of historical AA found in ancient chronicles or other archival documents. In the sources, depths were indicated making reference to specific levels recognizable by the Venetians, or were reported in ancient local units. The problem was that the starting level from which the depth was measured was obscure to us. Therefore, it was impossible to assess precise depths. After Cornaro

Table 2 The most extreme *Acqua Alta* in the documentary sources (revised after Enzi and Camuffo 1995). When more than one chronicle is reported, the text starts with §. Estimated depths are referred to the mean sea level of the current (contemporary) year. The last column reports the difference between the depth of historical AA (D_{Hist}) and the depth in 1966 (D_{1966}). Notes are indicated (${}^{\text{Number}}$) and reported at the end of the list. References are numbered [ref. number] and reported at the end of the Table. Transformations from local units to cm are indicated [Tr:]

Year	Summary of the original text in Venice units (with transformation to cm)	Estimated depth (cm)	$D_{\text{Hist}} - D_{1966}$ (cm)
1240	On streets, water reached the height of a man (1) [ref. 1, 2]	250?	+80?
1283	§ Water was higher than anyone could remember [ref. 3] § Water rose enormously [ref. 4] § Very high water, so that nobody could remain on the ground floor, but only on roofs [ref. 5] § Water reached the groin [ref. 6] § Water rose so much that boats went around San Marco Square [7] § Water rose more than 1 pace above CM [ref. 8] [Tr: (173.8 + 42) cm =216 cm]	> 216	> +46
1341	Water rose 1 pace above CM (2) [ref. 3] [Tr: (173.8 + 42) cm =216 cm]	216	+46
1342	§ Water rose 1 pace above CM [ref. 8] [Tr: (173.8 + 42) cm =216 cm] § Water rose 3 and more arms above CM [ref. 4, 5, 9] [Tr: (205 + 42) cm = 247 cm]	216 to 247	+46 to +77
1385	Water rose 8 feet (3) above CM [ref. 1, 2]; 8 feet = 278 cm	146?	−24?
1429	Water rose 5 feet above CM [ref. 1, 2] [Tr: (173.8 +42) cm = 216 cm]	216	+46
1443	§ Water rose 4 feet above CM [ref. 10] [Tr: (139 +42) cm = 181 cm] § Water rose 4 paces (4) above CM [ref. 1, 2]	181	+11
1517	Even though my courtyard is elevated, water reached 1 ½ foot [11]	> 150?	< −20?
1559	Water depth was 1 arm above streets [ref. 1,2] [Tr: 68.3 cm above streets]	> 168	< −2
1574	Water rose 1 arm above CM [ref. 1, 2] [Tr: (68.3+42) cm = 110 cm]	110	−60
1600	Boats could go around San Marco Square and many other streets [ref. 12]	160?	−10?
1686	§ Water reached the external floor of the small Loggia (5) in San Marco Square [ref. 13] § People went around the city by boat [ref. 1, 2]	170	0
1691	Water rose ½ foot less than in 1686 [ref. 13]	>> 155	<< −15
1727	Water reached the steps of the main altar of San Antonino church [ref. 1, 2, 5]	165	−5
1742	Water rose to such a high level, that people went by gondola to the public square [i.e., San Marco] [ref. 14]	> 160	<−10
1746	We went by gondola from Piazzetta [San Marco] to San Geminiano church; a foreigner went up and down San Marco Square, and there were other boats going around [ref. 1, 2, 15]	> 160	< −10
1750	On boat tours over San Marco Square, water rose up to the steps of the main altar in San Antonino church [ref. 1, 2, 15]	165	−5
1762	Boats and gondolas went over the streets and San Marco Square [ref. 16]	> 160	< −10
1770	Gondolas and boats went over San Marco Square [ref. 16]	> 160	< −10
1782	§ People went around San Marco Square by boat [ref. 17, 18] § No memory of a similar rise, covering three steps (6) of the Procuratie Nuove [ref. 17]	165	−5
1786	Boats on San Marco Square [19]	> 160	< −10
1802	Enormous AA in Venice; it reached 4 to 5 feet depth above San Marco Square [ref. 19] [Tr: 139 to 174 cm above the paving of the Square]	> 200	> +30
1821	Boats could ride around San Marco Square. The tide rose 3 feet and 5 ounces [Tr: 119 cm] above CM. [ref. 20] [Tr: (119 + 42) cm = 161 cm]	161	−9
1822	Water reached 1.30 m above CM [ref. 21]	172	+2
1848	Water rose to 1.40 m above CM [ref. 22]	182	+12
1859	The highest tide rose 0.88 m above CM [ref. 22]	130	−40

Table 2 (continued)

Year	Summary of the original text in Venice units (with transformation to cm)	Estimated depth (cm)	$D_{\mathrm{Hist}} - D_{1966}$ (cm)
1864	On January 14, 1867, the city was for the most part flooded by AA, which was only 5 cm less than the famous one in 1864 [ref. 23]	206	+36
1867	Water reached 1.59 m above CM [ref. 21]	201	+31

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MNL Marciana National Library, Venice

(1)Likely the early city level was lower, unknown. The depth remains uncertain

(2)Likely this event is misdated and occurred in 1342

(3)Likely 8 is a copy error for 3 feet = 104 cm

(4)Likely copy error of "pace" for "feet"

(5)Today the Loggia is 70 cm above the pavement of San Marco

(6)3 risers = 52 cm above paving; the depth 165 cm has been established considering 135 cm for the benchmark of San Marco in 1988 plus 30-cm land subsidence from 1782 to 1988 (page 6r), we know that the unknown reference was CM, and this is determined by the high tides plus the small waves. With these two findings, it has been possible to express the historical depths “above CM,” as well as above the MSL of the current (i.e., the contemporary) year. With homogeneous units and reference, it has been possible to compare the most extreme historical depths of the pre-instrumental period (1200–1870) with the most extreme one of the instrumental period (1871–today), i.e., the AA of 1966. It is known that this depth was 194 cm, but making reference to the Salute 1897 reference. In order to make homogeneous data, considering the land subsidence from 1897 to 1966 (i.e., 23.56 cm) (Carbognin et al. 1985), the AA of 1966 was 170.5 cm above the MSL of 1966.

The most extreme historical depths are reported in Table 2. Cases with undefined depths, as well as small depths (e.g., damage to wells or goods stored in warehouses) have been disregarded.

The estimated depths of the historical floods (i.e., column 3 of Table 2) have been represented in Fig. 4, making reference to the MSL of that time and comparing them with the 1966 level, also computed from the current MSL. The plot shows that the early period from 1200 to 1450 was characterized by several extreme cases, much more severe than 1966. This may be justified by three items, i.e., input of rivers, number of ancient inlets, and randomness.

6.2 The input of rivers

In the ancient times, a number of rivers entered the Lagoon, carrying the rainwater they collected in the inland catchment area. It must be considered that the AA is associated with the Sirocco Wind which causes heavy precipitation at Venice and its hinterland. To avoid silting, the Venetians made important hydraulic works to divert the rivers that entered the Lagoon (Filiasi 1796; Zendrini 1812; Miozzi 1957; Dorigo 1983; D’Alpaos 2010b). Cornaro disagreed with this policy because he was convinced that silting was mostly caused by the storm surges that originated turbidity offshore and then carried it into the Lagoon.

In 1324, the river Brenta was diverted with a southern path. In 1505–1507, the new canal Osellin collected and diverted to the east of Venice the water of the rivers Marzenego, Zero, and Dese. In 1530, after several partial diversions, the river Brenta was definitively diverted into the sea; the map by Sabbadino (Fig. 1a) dating 1543 shows this situation. In 1579, the river Piave started to be diverted into the open sea, but works continued for several years. In 1613, some other minor rivers, i.e., Botinico, Lusor, Brentella, and Musone, were diverted into Brenta. In 1683, the river Sile was diverted into the old bed of Piave, but with a new outlet leading to the open sea. In the 1840–1896 period, the river Brenta was temporarily brought back into the Lagoon, with some exceedingly high AA.

The lowering of the most extreme AA in the sixteenth century might be justified with the progresses of the hydraulic works and the reduction of the fresh water input that contributed to raise the water level inside the Lagoon. The new peak of the nineteenth century, when Brenta was temporarily brought back, seems to confirm this general relationship.

6.3 The Lagoon inlets

In the ancient times, the inlets were six (see the Sabbadino map in Fig. 1a), twice the present-day number. Cornaro (pages 11v–20r) noted that the regular tides were not turbulent, provided normal exchanges of clear water, and were effective in keeping clean the Lagoon, removing garbage, sewer, and any excess of silt. As opposed, the tides that exceeded CM were generated by storm surges; the associated turbulence caused

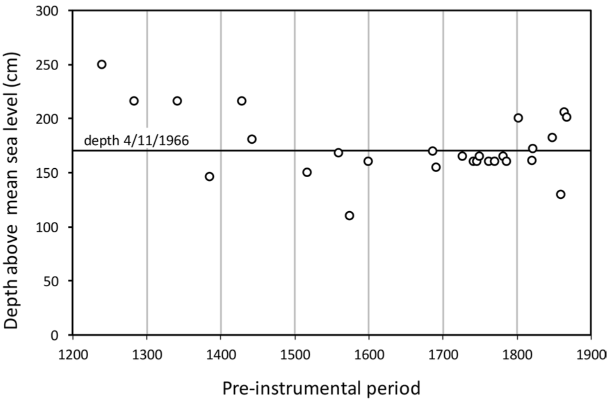

Fig. 4 Depth of the most extreme *Acque Alte* in the pre-instrumental period. Depths are counted from the mean sea level of the current year. The depth of the highest *Acqua Alta* over the instrumental period (4 November 1966) has been reported as a reference (continuous line)

coastal or bottom erosion, and the turbid waters were considered responsible of a net transport of silt from the sea. Once silt entered the Lagoon, the calm water allowed sand and mud to settle and deposit on the bottom. On the long run, canals were silted, impeding navigation and forcing periodic digging works. This observation convinced Cornaro that the input of water from the sea should be controlled.

Cornaro (pages 20r–26v) suggested the temporary closure of the main inlets, when waters entering the Lagoon exceeded the CM threshold, with two aims: to control silting and flooding depth. He was convinced that the inlets that had the largest cross sections gave a major contribution for the entrance of seawater and, ultimately, for the accumulation of water and its level in the Lagoon. He was especially concerned about the dynamic aspect; i.e., shallow waters will damp waves, while deep waters allow the free entrance of the rough sea. He commented that the exceptional flooding depths were due to water pushed by the sea, and if the cross sections of the inlets were reduced, also the storm forcing would have been reduced. He justified these thoughts by saying that in the past, the sea surges caused floods with higher depths that submerged the small islands. The plot of Fig. 4 seems to confirm with him. He wrote that, after the Malamocco inlet was reduced, the floods too were reduced (page 11r). Therefore, he suggested to take advantage of this discovery, i.e., the relationship between the flow through the inlets and the depth reached by the AA, and control the inlets.

Over time, the hydraulic works were carried out leading to two opposite directions: on the one hand, reducing the number of inlets that has been halved, on the other, increasing their cross sections. A comparison between the values of maximum flow across the three inlets in 1810 and 2010 (D’Alpaos 2010a) shows a substantial change: the maximum flow across Malamocco was almost twice, i.e., 208%, followed by Lido (i.e., 140%) and a minor one in Chioggia (i.e., 127%).

The idea of closing the inlets in the case of surges returned four centuries later with the MOSE (https://en.wikipedia.org/wiki/MOSE), i.e., the complex network of 78 mobile barriers designed to separate the Lagoon from the sea at the occurrence of storm surges. To date, MOSE is in the verification and testing phase and has been activated in November and December 2022; it is expected to be fully operational by October 2023.

6.4 Meteorological forcing

Another (random) variable is associated with the intensity and duration of the meteorological forcing, and the adverse combination of the factors contributing to the flooding depth, e.g., astronomical tide, wind drag, atmospheric pressure, and free oscillation of the Adriatic Sea basin (seiche). This balance has been extensively discussed for the floods in 2018 and 2019 stressing the relevance of the phase lag between the various components (Cavaleri et al. 2019, 2020; Lionello et al. 2020; Mikhailova 2021; Ferrarin et al. 2022). The intensity, as well as the (random) combination of the various components, had determined the past extreme depths and will continue with the future ones. This randomness may transform a normal in an extreme AA, or vice-versa, or may generate an unparalleled catastrophic flood.

It must be specified that the earliest extreme flood, in 1240, apparently was the most extreme of the series, i.e., the water on streets reached the height of a man, i.e., 160–170 cm; however, the early city level was unknown, and the real total depth (i.e., the sum of the two) remains uncertain.

7 Conclusions

Cornaro was not a scientist and was unable to support his views with theory, but his witness is precious. Cornaro wrote that the SLR occurred over the previous three centuries obliged the Venetians to raise the paving of the City and the ground floors of buildings and churches, as well as to build bridges with taller arches. This is a direct witness that the sea level was rising since the Middle Ages and that the City had to afford heavy public works to adapt and survive. In particular, this confirms that the sea level rose consistently, at least since 1260, when Venice was paved for the first time.

It has been possible to reconstruct how the Venetians perceived the sea level before the invention of the tide gauge. They noted that the sea made a natural mark on all quays and building walls, and associated the usual sea to the dark band of the algae. This level was named common mark or common marine level (CM) and used as an official reference, providing the zero for the quantitative measurement of the depth reached by seawater. All the buildings have their facade facing a canal, a stair connecting the entrance door with the canal, and all risers had a standard height of ½ foot. Water stairs constituted an early hydrometer of which every building was provided.

Knowing that the sea level was referred to CM, and the distance between CM and MSL, it has been possible to assess quantitative values to the historical surges starting from AD 1200. In addition, another proxy was used, i.e., the draught of the gondolas that could make a trip over San Marco Square when it was flooded. The result is that the most extreme depths occurred in the period in which the rivers entered the Lagoon bringing their water and the precipitation associated with the Sirocco Wind, which was collected over their inland catchment area. After the rivers were diverted out of the Lagoon, the most extreme depths became quite homogeneous, close to the value observed in 1966, i.e., the most severe flood over the instrumental period.

The documentary sources show that the AA in 1966 has not been the most extreme in the history of Venice. The deepest AA exceeded by 40 cm the 1966 reference, and Venice should be prepared to face again this risk. The impressive depths reached before 1500 may be justified by the contribution of the ancient rivers, but the random association of the various components that determine the AA level, may exceed the above threshold.

Cornaro suggested that the Lagoon inlets should be closed when surges raise the sea level above CM, but this was clearly impossible for the poor technology of that time. Nowadays, the same idea has been realized with the mobile gates of the MOSE system applied to the inlets. This method is under set-up and may provide an efficient solution for the short and medium term, provided that the level reached by the surge is timely and accurately forecasted and the barriers operated in time.

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Data availability The paper is grounded on the literature cited in the text and published in Table 2 and, more extensively, in Enzi and Camuffo (1995).

Declarations

Permissions to publish As indicated in the captions, by kind permissions of Internet Culturale, Marciana National Library, Venice (Fig. 1a and Fig. 4b); NASA Earth Observatory (Fig. 1b); Insula spa, Venice (Fig. 2b); and Paris Musées, Musée Cognacq-Jay (Fig. 3c).

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