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Perception and Reality: How the Depths of the High Waters in Venice Apparently Change with the Reference System

Dario Camuffo

National Research Council of Italy, Institute of Atmospheric Sciences and Climate, Corso Stati Uniti 4, 35127 Padua, Italy; d.camuffo@isac.cnr.it

Abstract: Over the centuries, the depths of the most severe storm surges that have flooded Venice have been measured using different reference frames, i.e., related to the algae belt (CM), mean sea level (MSL), local land (ZMPS), large-scale leveling (IGM), and satellite altimetry (SA). Some reference frames, i.e., IGM and SA, are absolute, while the others are relative and represent two different physical points of view, i.e., CM and MSL refer to the sea that is rising and ZMPS refers to the land that is subsiding. The perceptions derived from the different systems are contradictory. This paper discusses and compares surges from 1821 to 2021 measured with these frames, also including the commemorative plaques that report the flood depths on walls in Venice. The paper explains the consequences of a change in frame and zero reference, and it transforms the flooding depths from the original systems to make them homogeneous. The severity of flooding changes in terms of rating with the choice of frame. In the 19th century, five storm surges exceeded the famous level of 1966 and, if they were to recur today or in the future, the sea level rise and the local land subsidence that have occurred in the meantime would greatly exacerbate the situation.

Keywords: sea level rise; storm surges; flooding depth; reference frames; Venice

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1. Introduction

The depths of the most severe storm surges that have flooded Venice (Figure 1a,b) over the centuries [1,2], locally called '*Acqua Alta*' (AA, which means 'high water'), were measured with different reference frames [3–7]. The choice each time was partly determined by historical events and partly by scientific progress. The frames used were relative, being fixed to a mobile reference (i.e., mean sea level, or local land subject to subsidence), and constitute a complex topic that must be clarified and better understood in its historical context.

The extreme AA of November 1966 (Figure 2) made a profound impression because the water reached the highest level within living memory. Piazza San Marco was completely flooded, and the wooden walkways were not sufficient to face this emergency. This was the first and only time in which the Venetians of the 20th century could ride by boat in Piazza San Marco. The city suffered extensive damage and it was clear that, in the future, a similar or worse negative combination of synergistic factors could compromise the very survival of Venice.

Starting from 1966, the Italian Government enacted a series of special laws for Venice [8–10] to promote safeguarding actions and coordination, and, in 1969, the National Research Council of Italy (CNR) founded an Institute in Venice and for Venice, i.e., the Laboratory for the Study of Large Masses, where I worked from its inception. Particularly important was the appointment of the 'Comitato di Indirizzo Coordinamento e Controllo' (CICC, Steering Committee for Coordination and Control, nicknamed '*Comitatone*'), instituted with governmental decree in 1995 [8]. These experts had the task of deciding the main interventions on the lagoon inlets, including the system of mobile gates, named MoSE, to regulate exceptional tidal flows [11]. The committee planned research and works to be carried out and made decisions [10,11] by considering models and simulations based on the series of sea surges to date, i.e., the instrumental records, and historical reconstructions from documentary sources [3].

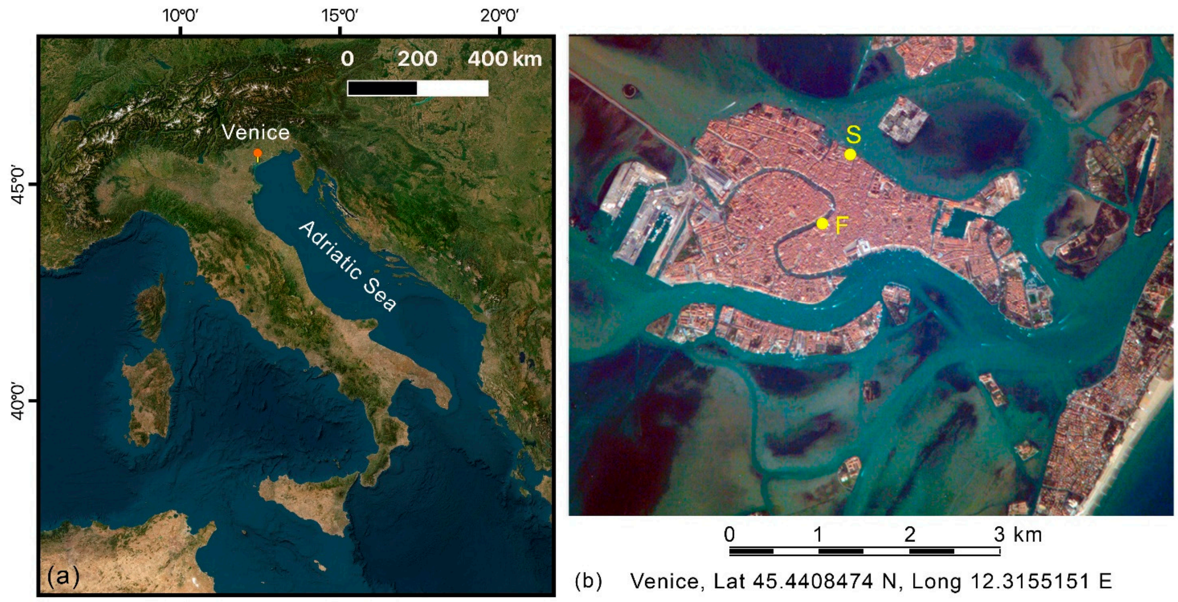


Figure 1. (**a**) Location of Venice on the northern side of the Adriatic Sea (image prepared using ESRI ArcGIS Pro 3.2 software; the data therein are derived from ESRI, Maxar, Earthstar Geographics, and the GIS User Community). (**b**) The city of Venice surrounded by lagoon water. F is for Ca′ Farsetti Palace and S is for Salizada dei Spechieri street, that are considered in this study (astronaut photograph ISS014-E-17346, 15 March 2007, provided by NASA, the ISS Crew Earth Observations experiment and the Image Science & Analysis Laboratory, Johnson Space Center).

Figure 2. San Marco Square with boats and wooden walkways during the Acqua Alta of 4 November 1966 (picture from unknown author, Wikimedia Commons).

After the dramatic AA of 1966, in 1968 and 1969, the United Nations Educational, Scientific and Cultural Organization (UNESCO) organized international meetings of experts and established an international system for the protection of monuments, groups of buildings, and sites of universal cultural interest, like Venice [12,13].

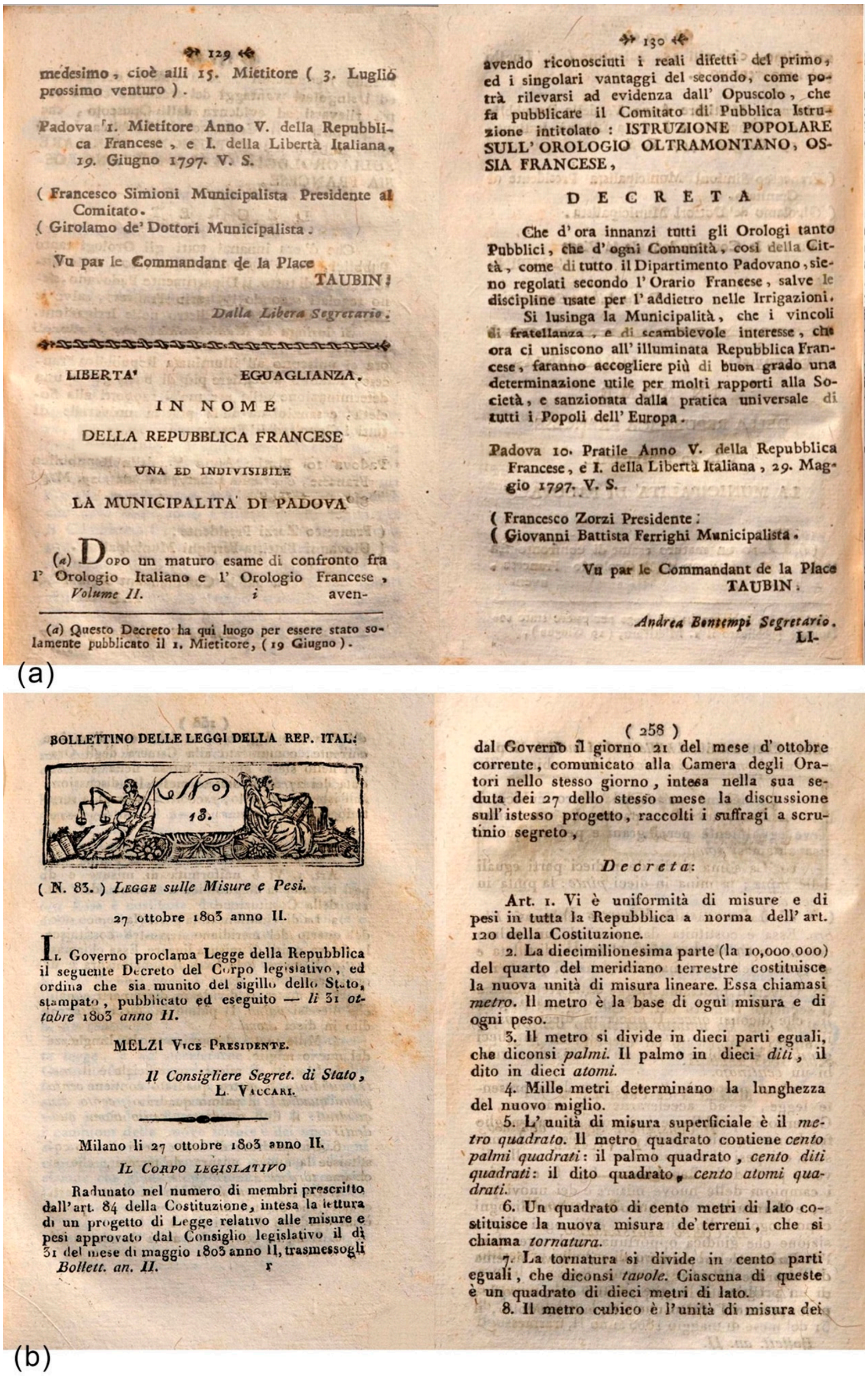
When shifting the focus from this catastrophic event to the general problem of storm surges in Venice, the series of AA events considered was multi-secular, and it was noted that the series could be correctly interpreted only if each was considered within its historical context, which produced significant changes in instruments, units, scales, and the zero reference.

Historically, the Most Serene Republic of Venice, named '*La Serenissima*', was a popular state based on maritime trade, which had a stable government, mercantile economy, and cultural interest for over a millennium. The history is well-known [14–16]. The Republic fell in 1797 to the invading troops of Napoleon Bonaparte, and with the Treaty of Campo Formio (17 October 1797), Napoleon ceded Venice and its hinterland to the Habsburg Austrians, but kept other parts of Italy (e.g., the Cisalpine Republic, the Ligurian Republic). In 1866, after the Third War of Italian Independence, Venice joined the newly formed Italian Kingdom. These political events changed and reorganized the life of Venice, including all public services and the way of measuring the sea level.

In the Most Serene Republic of Venice, there were no regular measurements of the sea level. The Water Magistrate and citizens made reference to the green belt of algae living on banks, named '*Comune Marino*' (CM, for Common Marine [Mark]), 'Common Tide', or simply 'Common' [5–7,17–23], and this was sufficient to recognize the level and phase of the tide, as well as to establish the exceptional depths reached by flood waters dragged by storm surges, as explained later (Section 4.1). The sea level, or the flooding depth, was expressed in local units, i.e., '*piede*' (the Venetian foot, 1 *piede* = 34.76 cm) and '*oncia*' (literally ounce, 1 *oncia* = 1/12 *piede* = 2.89 cm) [24]. The term '*oncia*' was used for linear measurements and not only for capacity or weight. The name was derived from the Latin '*uncia*', which was a small coin, 1/12 of the main coin, named '*as*'. The term '*oncia*' became synonymous with (1/12)th. Similarly, in Britain, the 'inch' is equal to 1/12 of a foot, and the troy 'ounce' is 1/12 of a troy pound.

In 1797, Napoleon abolished all local units and established that the hours and the day should be measured as in France, starting from midnight (Figure 3a) [25]. In Italy, according to the tradition of ancient Rome, the old day died with dusk, and from that moment, the new day and the counting of hours began [26]. Initially, the French style generated some confusion among people, who associated the end of the day with the disappearance of the light, which was an event and a specific time, variable with the season, clearly visible and recognizable by everyone. The choice of midnight was considered theoretical, and nobody could know when it arrived in order to set the clock [26]. Finally, with patience, time, and popular instruction, the new day began to start from midnight [27]. The next imposed step was to leave behind the local units of length, capacity, and weight based on anthropometric references (e.g., step cubit, foot, span, finger) and adopt the 'abstruse' metric system based on a fraction of length of a meridian, though very few knew what this was and barely anyone was able to imagine it [28,29]. On 27 October 1803, a general law was established (Figure 3b) for the whole Republic of Italy (i.e., the part of Italy under French occupation), where all measurements of length had to be reported in meters, and units of volume and weight had to be derived from the meter, e.g., a cubic meter, or representing the weight of a cubic decimeter of water [30].

During the Austrian domination from 1815 to 1866 [14], the Water Magistrate was appointed to monitor the sea level [7,18,31,32]. The tidal extremes were quantitatively measured every day in Rialto, headquarters of the Water Magistrate. Measurements were taken by visual inspection, i.e., reading the tide level on a graduated scale. Zero was the traditional CM reference, following the old, traditional style. The most relevant daily extremes, as well as some weather notes, were published in newspapers or in scientific bulletins, e.g., the *Bullettino Meteorologico del Collegio Romano*, Rome, or the *Bullettino Meteorologico dell'Osservatorio del R. Collegio Carlo Alberto in Moncalieri*.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medesimo, cioè alli 15. Mietitore (3. Luglio prossimo venturo).

Padova 1. Mietitore Anno V. della Repubblica Francese, e I. della Libertà Italiana, 19. Giugno 1797. V. S.

(Francesco Simioni Municipalista Presidente al Comitato.
(Girolamo de' Dottori Municipalista.

Vu par le Commandant de la Place
TAUBIN.

Dalla Libera Segretario.

LIBERTA' EGUAGLIANZA.

IN NOME

DELLA REPUBBLICA FRANCESE

UNA ED INDIVISIBILE

LA MUNICIPALITA' DI PADOVA

(a) Dopo un maturo esame di confronto fra l' Orologio Italiano e l' Orologio Francese,

Volume II. i aven-

(a) Questo Decreto ha qui luogo per essere stato solamente pubblicato il 1. Mietitore, (19 Giugno).

130

avendo riconosciuti i reali difetti del primo, ed i singolari vantaggi del secondo, come potrà rilevarsi ad evidenza dall' Opuscolo, che fa pubblicare il Comitato di Pubblica Istruzione intitolato: ISTRUZIONE POPOLARE SULL' OROLOGIO OLTRAMONTANO, OSSIA FRANCESE,

DECRETA

Che d' ora innanzi tutti gli Orologi tanto Pubblici, che d' ogni Comunità, così della Città, come di tutto il Dipartimento Padovano, sieno regolati secondo l' Orario Francese, salve le discipline usate per l' addietro nelle Irrigazioni.

Si lusinga la Municipalità, che i vincoli di fratellanza, e di scambievole interesse, che ora ci uniscono all' illuminata Repubblica Francese, faranno accogliere più di buon grado una determinazione utile per molti rapporti alla Società, e sanzionata dalla pratica universale di tutti i Popoli dell' Europa.

Padova 10. Pratile Anno V. della Repubblica Francese, e I. della Libertà Italiana, 29. Maggio 1797. V. S.

(Francesco Zorzi Presidente.
(Giovanni Battista Ferrighi Municipalista.

Vu par le Commandant de la Place
TAUBIN.

Andrea Bontempi Segretario.

LI-

(a)

BOLLETTINO DELLE LEGGI DELLA REP. ITAL.

N° 13.

(N. 83.) *Legge sulle Misure e Pesi.*

27 ottobre 1803 anno II.

Il Governo proclama Legge della Repubblica il seguente Decreto del Corpo legislativo, ed ordina che sia munito del sigillo dello Stato, stampato, pubblicato ed eseguito — *li* 31 *ottobre* 1803 *anno II.*

MELZI Vice Presidente.

Il Consigliere Segret. di Stato,
L. Vaccari.

Milano li 27 ottobre 1803 anno II.

Il Corpo legislativo

Radunato nel numero di membri prescritto dall'art. 84 della Costituzione, intesa la lettura di un progetto di Legge relativo alle misure e pesi approvato dal Consiglio legislativo il dì 31 del mese di maggio 1803 anno II, trasmessogli

Bollett. an. II. r

(258)

dal Governo il giorno 21 del mese d' ottobre corrente, comunicato alla Camera degli Oratori nello stesso giorno, intesa nella sua seduta dei 27 dello stesso mese la discussione sull' istesso progetto, raccolti i suffragi a scrutinio segreto,

Decreta:

Art. 1. Vi è uniformità di misure e di pesi in tutta la Repubblica a norma dell' art. 120 della Costituzione.

2. La diecimilionesima parte (la 10,000 000) del quarto del meridiano terrestre costituisce la nuova unità di misura lineare. Essa chiamasi *metro*. Il metro è la base di ogni misura e di ogni peso.

3. Il metro si divide in dieci parti eguali, che diconsi *palmi*. Il palmo in dieci *diti*, il dito in dieci *atomi*.

4. Mille metri determinano la lunghezza del nuovo miglio.

5. L' unità di misura superficiale è il *metro quadrato*. Il metro quadrato contiene *cento palmi quadrati*: il palmo quadrato, *cento diti quadrati*: il dito quadrato, *cento atomi quadrati*.

6. Un quadrato di cento metri di lato costituisce la nuova misura de' terreni, che si chiama *tornatura*.

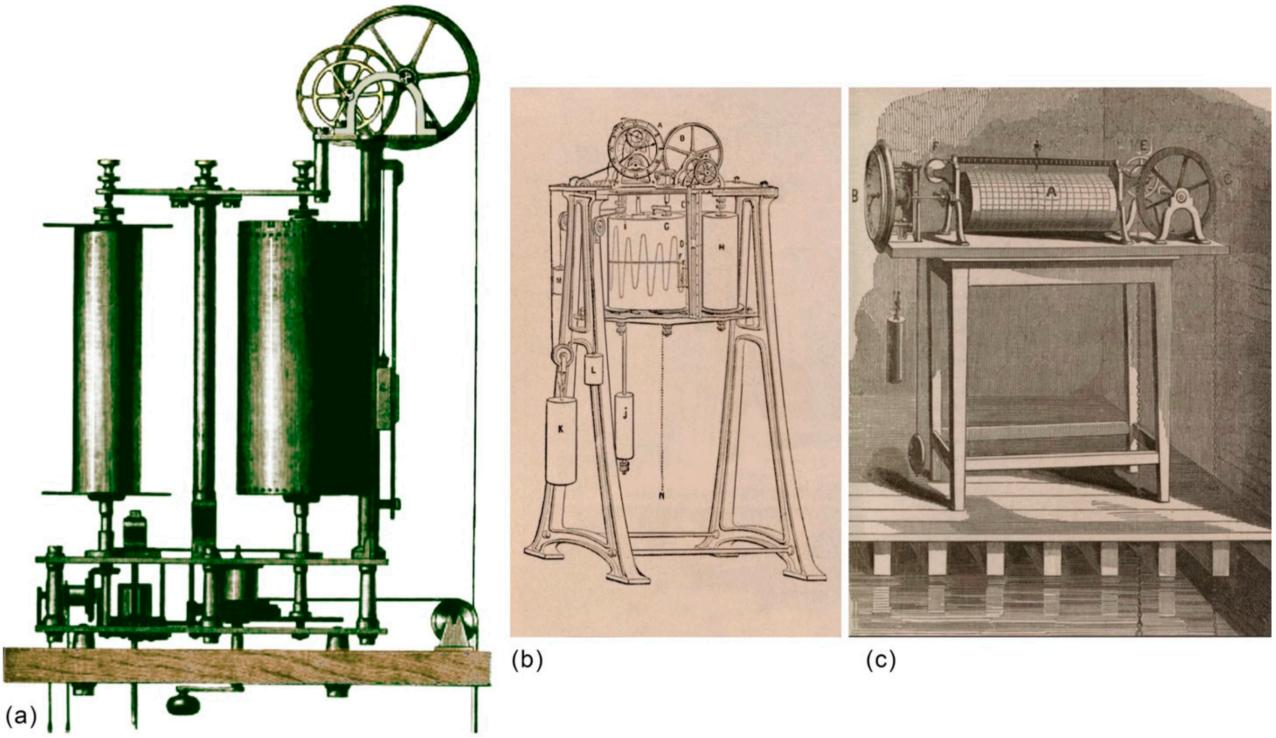
7. La tornatura si divide in cento parti eguali, che diconsi *tavole*. Ciascuna di queste è un quadrato di dieci metri di lato.

8. Il metro cubico è l' unità di misura dei

(b)

Figure 3. Pictures of the front pages of the original historic Napoleonic decrees on measurements and the newly imposed units. (**a**) The Decree of 29 May 1797 [25], which orders the people to abandon the Italian time (starting from twilight) and adopt the French one (starting from midnight). (**b**) The first two pages of Law N. 83, 27 October 1803 [30], on measurements and weights. The heading 'Bulletin of Laws of the Republic of Italy' refers to the Italian territory under French occupation.

Starting from October 22, 1866, when Venice joined the Italian Kingdom, all public services had to be reorganized. This period is documented by a number of contemporary sources and some recent papers [2,22,32–46], and it can be summarized as follows. The Water Magistrate was relieved of the duty of measuring the tide. This task was initially assigned to the 'Istituto Veneto di Scienze Lettere e Arti' (i.e., Venetian Institute of Sciences, Letters, and Arts) and then to the Municipality of Venice. In 1871, a recording tide gauge was installed in Palazzo Loredan, headquarters of the Institute, and the scale was fixed to the structure that housed the tide gauge. In 1906, another tide gauge was installed at Punta della Salute, on the side of the Grand Canal. The year 1871 was a turning point, not only for the regular service, including recording, but also because the tide gauge readings changed the reference frame, from the CM to the so-called 'Zero Mareografico Punta Salute' (ZMPS, which means: Zero tide level of Punta Salute), linked to the local land. A network of tide gauges was installed to monitor Venice and the lagoon. The most accurate instrument of the network, which was used in Venice and in Punta Lido, was the William Thomson recording tide gauge model with a 1/5 reduction ratio, ink pen, and weekly strip chart record (Figure 4a) [6,22,43]. In a note of the Hydrographic Office, Venice, dated 1912, it is stated that this tide gauge was built by Negretti & Zambra, London [44]. However, it is slightly different from the figure of the improved Sir William Thomson self-recording tide gauge model with vertical drums in the Negretti & Zambra (1885) catalogue [45] published 14 years later (Figure 4b). The same catalogue reports, in addition, an improved Newman model self-recording tide gauge with horizontal drums (Figure 4c). Similar instruments were used for the other stations of the lagoon network. The Thomson model was more expensive than the Newman model, i.e., GBP 95 and GBP 50, respectively, in 1885. This explains why two models were used, with the most precise ones in the key locations, while the extensive lagoon network was furnished with cheaper instruments.



(a) (b) (c)

Figure 4. (**a**) The self-recording Thomson model tide gauge used in Venice and S. Nicolò Lido since 1871 [21]. (**b**) The Thomson model vertical drums in the 1885 Negretti & Zambra catalogue [45]. (**c**) The Newman model horizontal drum in the same catalogue. Please note that (**b**,**c**) are pictures of an original old catalogue, and include some letters referred to technical details and spare parts not relevant to us.

When the Venetians adopted the CM reference and then the ZMPS (see later Section 4.3), they believed that these frames were absolute. In reality, both of them are relative, and each system considers its own reference (i.e., the sea or the land) unchangeable over time and the other (i.e., the land or the sea) mobile. Sea level rise (SLR) and local land subsidence (LLS) have caused the two frames to be in relative motion, which leads to confusion when comparing data, especially because the departure increases with time. This makes it difficult to compare early to modern data, as well as to perceive the real depth reached during storm surges.

In 1942, the 'Istituto Geografico Militare' (IGM, the Military Geographic Institute, see later Section 4.4) introduced a further frame, this one based on a large geographical domain including the whole of continental Italy, in order to obtain a stable reference over the land and the coastline [41,47,48].

Recently, a further absolute frame, i.e., satellite altimetry, has appeared [49] (see later Section 4.5). Satellite altimetry started in 1992 with the TOPEX/Poseidon mission. The NOAA/NEDIS/STAR Laboratory for Satellite Altimetry is involved in a wide range of oceanographic and climate studies, including those of internal tides [50].

Venice is frequently exposed to AA coastal floods. Storm surges are the main drivers of the floods, in association with astronomic tides, free oscillations of the Adriatic Sea, and other forcing factors associated with wide-scale atmospheric or oceanic oscillations [1–3]. However, the most extreme storm surges that have flooded Venice cannot be directly intercompared because they were recorded with different frames. To remedy that, in this paper, the most severe storm surges that have flooded Venice in the last two centuries are made homogeneous, analyzed, and discussed in light of the various old and modern frames, either linked to the sea or the land, which have been used in Venice. The selected period is the best documented one, which includes the AA events from 1821 to 2021. The upper limit of 2021 represents the start of operations of the protective system composed of mobile barriers, called MoSE [51], affecting the natural sequence of flooding surges.

The reference frames that have been used in Venice to measure the sea level and the flooding depths are of various types, either relative or absolute. Relative frames may be linked to the mean sea level and, therefore, perceive the sea as constant and the land as mobile, or vice versa, while absolute frames are able to distinguish the individual movements of the sea or the land. The historic and the modern reference frames used in Venice, as well as their main features, are presented in Table 1. Their characteristics will be extensively explained and discussed in Section 4.

The first aim of this paper is to clarify the differences between the historic and the modern frames for expressing the sea level in Venice. Two frames, namely the historic CM and the modern MSL, are linked to the sea, while another two, namely the ZMPS and the IGM, are linked to the land, the former on the local scale and the latter on the large scale. Emphasis will be given to the most commonly used systems.

The second aim is to provide time-dependent equations for transforming readings from marine (i.e., CM and MSL) to land-linked frames (i.e., ZMPS and IGM), and vice versa, to make all readings homogeneous. Then, the most extreme surges, and their flooding depths, will be compared in both frames, to clarify how the severity rating is affected by the choice of frame.

The final aim is to consider the most severe storm surges that had flooded Venice in the last two centuries, either archived as instrumental records or commemorative plaques, and explain how the choice of the reference frame can have consequences in determining the flooding depth and its perception.

Table 1. Reference frames used in Venice to measure the sea level and the flooding depths, whether the frame is relative (R) or absolute (A), and whether the sea level or the land is perceived constant or mobile. The last column gives the resolution capability, i.e., whether the perceived movement is interpreted as the bulk sum of the individual movements of the sea and the land (∑(SLR + LLS)) or whether these two movements are distinguished and recognized individually.

Frame	Extended Name	Starting Date	Reference	R/A	Perceived Constant	Perceived Mobile	Resolution Capability
CM	Common Marine Mark	since antiquity	algae belt (high tides + waves)	R	MSL	local land	bulk sum ∑
MSL	Mean Sea Level	19th century	MSL	R	MSL	local land	bulk sum ∑
ZMPS	Zero Mareografico Punta Salute	1897	local land at Punta Salute	R	local land and buildings	MSL	bulk sum ∑
IGM	Istituto Geografico Militare	1942	continental Italy	A	continental Italy	MSL and LLS	individual movements
SA	Satellite altimetry	1992	distance between the orbit and the geoid	A	orbit distance	MSL and LLS	individual movements

2. Materials and Methods

The AA surges that occurred before 1871 are presented elsewhere [4,7]; information on those after 1871 is provided by the Italian Institute for Environmental Protection and Research (ISPRA) and the Tide Forecasting and Reporting Centre of the Municipality of Venice.

In the period from 1820 to 1870, the CM and the mean sea level (MSL) of the current year t_{yr} were reconstructed using an exponential equation [6,52], expressed in cm and ZMPS units:

$$\mathrm{MSL}(t_{yr}) = -154.6 + 6.7(\exp 0.001653\ t_{yr}). \tag{1}$$

Equation (1) was derived from a multiproxy series that is seven centuries long [6,52]. However, in the short period from 1820 to 1897, using linear approximation is also effective, i.e.,

$$\mathrm{MSL}(t_{yr}) = 0.24\ (t_{yr} - 1897) \tag{2}$$

where =0.24 cm/year is the bulk average of the relative sea level rise rate, which includes the eustatism and LLS in that period. The rationale of Equation (2) is based on well-known geometric properties of secants. Given an arbitrary function F(t), on a selected interval Δt from t_1 to t_2, the secant to F(t) is defined by the points intersecting with coordinates (t_1, F(t_1)) and (t_2, F(t_2)). The slope of the secant represents the average rate of change in F(t) in the interval Δt. In addition, if Δt is sufficiently small, the secant gives a good approximation of F(t) in that interval. In this specific case, F(t) is MSL(t_{yr}), t_1 = 1820, and MSL(1820) = −18.8 cm; t_2 = 1897 and MSL(1897) = 0. Equation (2) is the equation of the straight line passing through the two points with coordinates (1820, −18.8) and (1897, 0). The advantage of using a secant is that it is easier to compute a linear equation than an exponential one. In the named interval Δt, the maximum departure between the exponential and the secant approximation is 3 mm. Other 3 mm uncertainty should be added for Equation (1).

When consulting Italian and foreign newspapers and illustrated weekly magazines of the 19th century, I found useful data in GAZZETTA DI VENEZIA, IL DIAVOLETTO (printed in Trieste), EMPORIO PITTORESCO (printed in Milano), and L'ILLUSTRATION, JOURNAL UNIVERSEL (printed in Paris), as shown later. A note is needed for the AA of 1864. The newspapers GAZZETTA DI VENEZIA and IL DIAVOLETTO (which relied on the GAZZETTA DI VENEZIA) reported that the AA of 15 January 1867 was 159 cm above CM, and that such a level was 4 cm less than in 1864. Therefore, in this and in a previous paper [7], the 1864 AA has been considered 159 + 4 cm = 163 cm. However, Torelli (1870) [53], Contin (1882) [54], and some others think that the AA of 1867 reached the maximum value. This suggests a misprint for 1864. Should it be interpreted as meaning 4 cm "more" instead of "less", i.e., 155 cm? In 1867, a debate ensued between Zantedeschi, Secchi and Beltrame [19], and the level in 1867 was confirmed, while that in 1864 was not. I have been unable to find the original 1864 reading to confirm or correct this depth. Fortunately, the difference (4 cm) is relatively small.

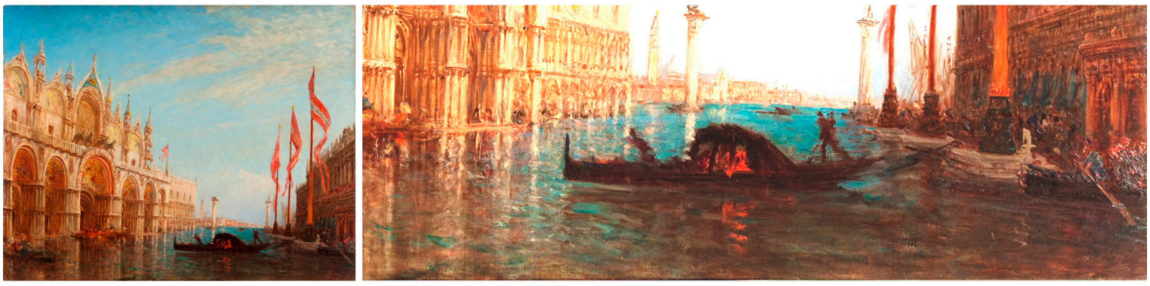
In addition to written sources, visual documentation is precious, and a number of paintings illustrate the most exceptional AA events, as shown in Section 3. The old Venetian reference based on the CM, as well as the ZMPS and other present-day systems, and the related equations for measurement and conversion, are discussed in Sections 4 and 5.

3. Presentation of the Visual Documentation and Comments

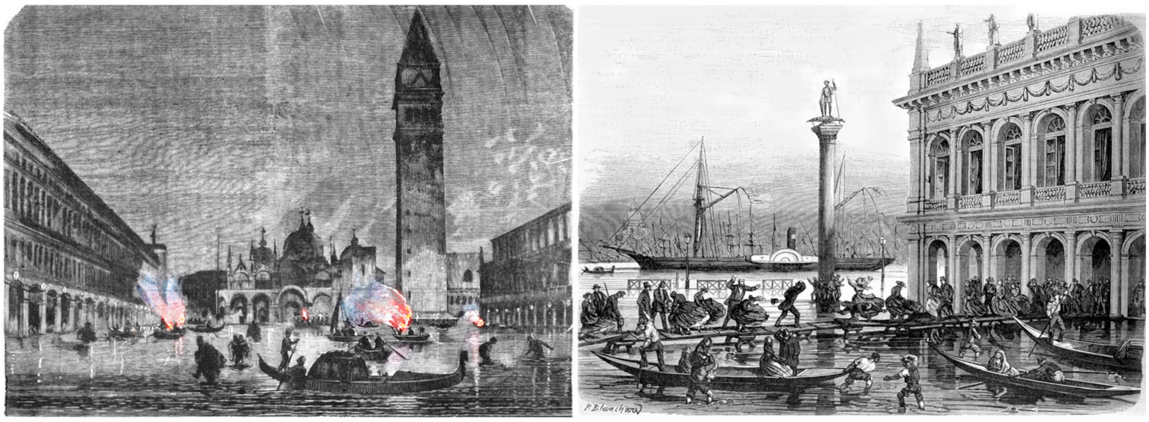
In the 19th century, some paintings illustrated an exceptional situation where gondolas and other small boats could navigate in Piazza San Marco (Figure 5). Surprisingly, such paintings were only created in the 19th century, and not in the previous period, including the 18th century, when painters of Vedutas represented the urban environment, recording instances of usual and unusual life, e.g., when the lagoon was frozen over. The first painting (Figure 5a), by Vincenzo Chilone, was produced in 1825 and shows boats on the Piazza. It is estimated that a gondola requires 60 cm of water to navigate [7,55]; however, no people are walking or playing in the water, suggesting that the flood water was too deep to allow these activities. The second painting (Figure 5b), by Federico Moja, was created in 1853 and shows boats as well as people walking with their calves immersed in the water. The third painting (Figure 5c), by Felix Ziem, shows boats but no walking people. According to the Petit Palais, Musée des Beaux-arts de la Ville de Paris, where the painting is located, it was produced after 1863. Moreover, it was certainly concluded before 1866, because some red and white Austrian flags are visible, like in Chilone and Moja, and this excludes any date after 22 October 1866, when Venice joined Italy. Later, between 1880 and 1900, Ziem crafted a further painting, entitled 'Inondation à Venise' (flood in Venice, work identity no. 226280), hung at the Musée des Beaux-Arts, Paris. However, the view is from the Basin, and it is impossible to see what was happening on the squares and streets. In Figure 5, the next two images have been taken from weekly magazines. The former, Figure 5d, is from the EMPORIO PITTORESCO (printed in Milano) and represents the evening of 15 January 1867, with boats and people with torches emitting light and smoke. The latter, Figure 5e, is from L'ILLUSTRATION, JOURNAL UNIVESEL (rinted in Paris) and represents the morning of 16 January 1867, with boats, people walking through water, and wooden walkways as they are used today. The AA of 1867 was very famous, with announcements and drawings published in national as well as in foreign journals.

(a) Vincenzo Chilone

(b) Federico Moja



(c) Felix Ziem



(d) Borgomanero (e) Del Don - Blanchon

Figure 5. The most exceptional surges of the 19th century, when gondolas could float in San Marco Square. (**a**) Vincenzo Chilone, AA of 9 December 1825. Painting and detail with boats. (Source: Wikipedia, Photographer: AskArt. Unknown owner.) (**b**) Federico Moja, painted 1853. Painting and detail with boats. (Source: Web Gallery of Art, created by E. Krén and D. Marx. Private collection, fair use.) (**c**) Felix Ziem, painted between 1863 and 1866. Painting and detail with boats. (Paris Musées, Petit Palais, Musée des Beaux-Arts de la Ville de Paris, license CCØ.) (**d**) Evening of 15 January 1867, boats with torches in Piazza San Marco. (Engraving by Borgomanero, correspondent of the weekly magazine Emporio Pittoresco, N. 129 of 17 February 1867.) (**e**) Morning of 16 January with boats and (raised platform) wooden walkways in Piazzetta San Marco. (Engraving by P. Blanchon, after a drawing by M. del Don, foreign correspondent of the weekly magazine L'Illustration, Journal Universel, N. 1249, 2 February 1867.)

4. Presentation of the Different Frames Used in Venice and a Discussion of the Consequences Derived from the Definitions

4.1. The Historic CM, a Relative Frame Related to Sea Level

In 1560, Alvise Cornaro, in his '*Treatise on Waters*' (1560) [17], which has been discussed in another paper [7], explained the tidal mechanism of the time and its traditional use, which are summarized as follows: The sea water ordinarily rises 2 feet (i.e., 69.52 cm) every six hours and then decreases to the low level, and this is repeated every day of the year. The effect of this periodic tidal movement is that water generates a dark band of algae on the canal banks, and the upper edge of this band is named 'the sign of common' or 'marine common mark', indicated C or CM. When tides reach this level, they are said to be 'common' or 'as usual', and this happens when the sea is calm and there are no winds. When storms occur and strong winds blow, the sea water is dragged toward Venice, and the sea level increases by one, two, or three feet (i.e., 34.76 cm, 69.52 cm, and 104.28 cm), or more, depending on the storm strength. This extraordinary level is called 'above common' or 'above the common mark', and it can be also named 'above the ordinary' or 'extraordinary'. In this case, the sea is rough and the water is turbid, with silt in suspension, removed from the bottom and the shore ([17] pages 6v, 6r). Cornaro noted that, in the last three centuries before his time, the sea, and the CM as well, had risen continually, making it necessary to raise quays and the street paving by three feet, as well as demolish and rebuild bridges that no longer allowed the passage of boats ([17] pages 9r, 10v, 10r).

The CM reference has a number of advantages: it is natural, strictly related to the sea level; it is ubiquitous even in the most remote and unmanned locations; it is clearly defined and recognizable. When the magistrates responsible for public works established that the heights of banks, arches of bridges, or any other works built had to be a certain number of feet above CM, this level was easily controlled. The Venetians realized that the sea level had changed and continued to change, so in the 18th century, they began to fix benchmarks in white Istrian stone, with an engraved 'C' or 'CM' and a horizontal line to exactly define the 'common' sea level.

In Venice, all transport was by boat, every house had a staircase on the canal, and all steps were standardized, with the rise set at a ½ foot [56]. When the sea level exceeded the CM, the height reached was easily recognizable to everyone, because it was sufficient to count how many steps were submerged by the flood waters [7,55]; for example, four steps (i.e., 2 feet) corresponded to ≈70 cm; five steps ≈ 87 cm; six steps (3 feet) ≈ 105 cm. The Venetians could evaluate the tidal level and the depth reached by flood waters simply by looking at the departure between the water surface and CM.

The CM belt was the most obvious reference in past centuries. However, in modern times, a variant of this, i.e., the MSL, has been adopted in scientific and popular use.

The SLR and LLS changed the initial relationship between the sea, the landscape, and the built environment. In the case of a stationary sea level, the CM-related frame is equivalent to a system linked to the local land or the buildings. However, in the long-term, the relative sea level rises, and any reference linked to the CM considers the sea always at the same level, and so it perceives the land and its buildings as sinking. In the opposite case, a land-linked reference (e.g., a benchmark engraved on the canal bank) considers the land as stable and perceives the sea and the CM as rising, as is the case with the ZMPS frame.

4.2. The MSL, a Relative Frame Strictly Related to CM

In Venice, from the remote past till 1870, the sea level was indicated as a depth above or below the biological mark CM. Algae are phototrophic, so they require water, light, and oxygen, even if supplied at different times during the day [57]. In the *Dictionary of Venetian Words*, Mutinelli (1851) [21] defines the term 'Common' as the limit usually reached by sea waters within their regular cycles. It was commonly thought to coincide with the level of high tides [22,58], which would be true in the complete absence of waves ("when the sea is calm", as Cornaro said [17]), but it was never exactly measured before 2017. It has been found that the CM is, in fact, the sum of two contributions, i.e., the high tides that constitute the baseline, to which small waves generated by wind or local traffic should be added [5,6]. The average high tide level is 30 cm above the MSL. Wind or traffic waves, however, raise the wetting level. Intensive measurement has revealed that in the Grand Canal, the traffic generates waves of 17 cm additional wetting, while, in non-trafficked areas, the wave contribution is 12 cm [6]. Therefore, CM is related to MSL by the equation,

$$\mathrm{CM} = \mathrm{MSL} + \Delta\mathrm{H} \tag{3}$$

where ΔH is the additional wetting level reached by high tides and local waves, i.e., ΔH = 47 cm with motorboat traffic and ΔH = 42 cm without traffic. The latter value is consistent with ΔH around 40 cm proposed by Tono, Director of the Patriarchal Observatory, Venice, in 1889, with very modest traffic [59]. Tono noted that CM was above the average high tide level, and supposed to be related to the most extreme spring tides (i.e., new or full Moon). However, these occur twice a month and cannot keep the surface always wet as the algae require.

4.3. The ZMPS 1897 Frame: A Relative Frame Related to the Local Land, Affected by Subsidence

In 1871, when the first tide gauge was installed, a temporary scale was established by calculating the CM as the average of the astronomical high tides of the year 1825, and zero was set at 1.5 m below it to avoid negative values [39,54,60]. The zero level was later revised, considering a 25-year record, from 1885 to 1909. Zero was set at the mean sea level of that period, and was called the ZMPS or 'Zero 1897', from the central year of this reference period. Since then, all tidal measurements in Venice have made reference to the ZMPS. This frame is fixed to a built structure grounded on the local land, and it perceives the land as stable over time. The ZMPS was devised as a fixed frame but, in reality, it is mobile because it follows the LLS, meaning it is another relative frame.

It should be remembered that the LLS reported in the literature lies in the range of between 0.9 and 1.4 mm/year, with a median of 1.15 ± 0.25 mm/year (see bibliographic references quoted in [61]). The LLS worsened in the period from 1930 to 1970, in which sinking due to groundwater withdrawal reached 12 cm; however, this was followed by a 2 cm rebound, so the net loss was 10 cm [62].

4.4. The IGM 1942 Frame: An Absolute Frame Related to Land Unaffected by Subsidence

The Istituto Geografico Militare (IGM), which is responsible for Italian cartography, established a high-precision leveling network, constituting more than 20,000 benchmarks. In 1942, the IGM established the official reference, linked to the whole Italian territory, called 'Zero IGM' [2,41,47,48]. In the IGM system, Italy is covered with four specific frames, i.e., 'Genova 1942' for the continental peninsula, including the coasts and the network of all the tide gauges, and three for the islands, i.e., 'Cagliari 1965' for Sardinia, 'Catania 1956' for Sicily, and 'Lampedusa 2005' for the Pelagie Islands [48].

In Venice, the difference between the ZMPS and Genova 1942 reached 23.56 cm in 1968 [41]. Both the ZMPS and Genova 1942 are linked to the land, but Genova is stable while Venice is affected by marked subsidence, and the difference between the two frames must be calculated when precise conversions are needed, accounting for the LLS in Venice occurred until the selected year. The short explanation provided by the Municipality of Venice (https://www.comune.venezia.it/it/content/riferimenti-altimetrici, accessed on 1 March 2024) for the conversion between the ZMPS and Genova 1942 gives the difference for 1968, i.e.,

$$\Delta(\mathrm{IGM–ZMPS}) = 23.56\ \mathrm{cm} \tag{4}$$

without specifying that a further, important adjustment should be made for the LLS that has occurred meanwhile. In the modern period after 1970 (when water pumping was prohibited), the adjustment Δ(IGM–ZMPS) for the current year t_{yr} is given by

$$\Delta(\mathrm{IGM–ZMPS}) = 23.56 + 0.15 \times (t_{\mathrm{yr}} - 1968) \tag{5}$$

so that, today, t_{yr} = 2024 and Δ(IGM–ZMPS) ≈ 32 cm. Meanwhile, in the period before 1968, the formula should be adjusted with the previous values and the anomalous LLS.

The IGM frame 'Genova 1942' holds for Venice and the lagoon, but the traditional use of the ZMPS has prevailed (although with some exceptions), and it is still officially used by the Venice Municipality for Measurements, Alerts, and Forecasting. Therefore, the Venice dataset is usually converted from the ZMPS to the IGM frame (often using Equation (4)) when compared with other Italian stations or used in an international context. This fact may generate confusion for anyone who is not familiar with the local use.

4.5. Satellite Altimetry: An Absolute Frame Related to the Geoid

Satellite altimetry is the most recent absolute frame [49,50]. Altimetric data need specific corrections concerning the distance between the satellite and the surface of the Earth, and the calculation of the surface height should also include all corrections due to environmental conditions.

At present, the NOAA has published the plot of the Adriatic Sea mean sea level from 1992 to 2022, obtained by combining Topex, ERS-2, GFO, Envisat, Jason-1, Jason-2, and Jason-3 [50]. In this period, the absolute trend of SLR of the Adriatic Sea is +2.1 ± 0.4 mm/year [50]. If one considers the relative trend of SLR in Venice for the same period, the relative SLR (i.e., eustatism plus LLS) from the tide gauge is +3.1 ± 0.5 mm/year, from which the average LLS rate, i.e., –1.15 ± 0.25 mm/year, should be subtracted to obtain the absolute rate [52]. This gives (+3.1 − 1.15) ± 0.5 mm/year = +1.95 ± 0.5 mm/year, in excellent agreement with +2.1 ± 0.4 mm/year.

5. Results: Comparison between Different Frames, Perception and Reality

5.1. Comparison between CM, MSL and ZMPS

In the historic CM reference system, the depth $\mathrm{HAA_{CM}}$ reached by AA was expressed as a sum of two components, i.e., a baseline represented by CM, variable over the years, and a short-term peak formed by the excess water ($\mathrm{EW_{CM}}$) added to the baseline:

$$\mathrm{HAA_{CM}} = \mathrm{CM} + \mathrm{EW_{CM}} = \mathrm{MSL} + \Delta\mathrm{H} + \mathrm{EW_{CM}} = \mathrm{MSL} + \mathrm{EW_{MSL}} \tag{6}$$

where $\mathrm{EW_{CM}} = \mathrm{EW_{MSL}} - \Delta\mathrm{H}$. If CM, or MSL, is measured starting from the ZMPS, then there is no need for corrections.

This formula reproduces the definition given by Cornaro, i.e., AA is the depth reached by stormy waters above the CM, i.e., Equation (1) with the MSL of that year. Although the most popular use is to express the MSL as the 11-year running average, in this specific case, the average of the current year is preferred to be consistent with Cornaro and the old use of CM as determined by the current year. For the years in which CM is missing, the CM, or the MSL, can be calculated with the best-fit exponential equation (i.e., Equation (1)) representing the SLR [6,52], as in Figure 6 and Table 2. The difference between the MSLs of the individual years, and the interpolation over the entire series, may reach a few centimeters.

Returning to the comparison between the two reference frames, i.e., the old CM and the ZMPS, the key point is that the CM (and the MSL, which is linked to the CM) from one side and the land level from the other side are not stable over time, but should be updated with the value of the current year. The difference between the two frames becomes evident when comparing AA events in different time periods. The situation is illustrated in Figure 6, which includes (i) the $\mathrm{HAA_{ZMPS}}$ levels reached by AA events, as recorded on building walls (in the figure, $\mathrm{HAA_{ZMPS}}$ is the distance between the depth of the flood water, i.e., the '-'mark, and the ZMPS horizontal baseline); (ii) the value of the water exceeding the MSL ($\mathrm{EW_{MSL}} = \mathrm{HAA} - \mathrm{MSL}$) of the current year (in the figure, $\mathrm{EW_{MSL}}$ is indicated with blue dots, while $\mathrm{EW_{ZMPS}}$ is the distance between the blue dots and the green dots); (iii) the MSL of the year in which the AA occurred (green dots); (iv) a curve interpolating the tidal series of Venice (green line); and (v) a red dashed line parallel to the green line, but passing through the cloud of the AA of 1800, indicating how these historic floods would appear today, after the rise in relative sea level, if the same combination of forcing factors was repeated, with the same intensities and phases. Blue arrows connect the blue dots to the related level marks.

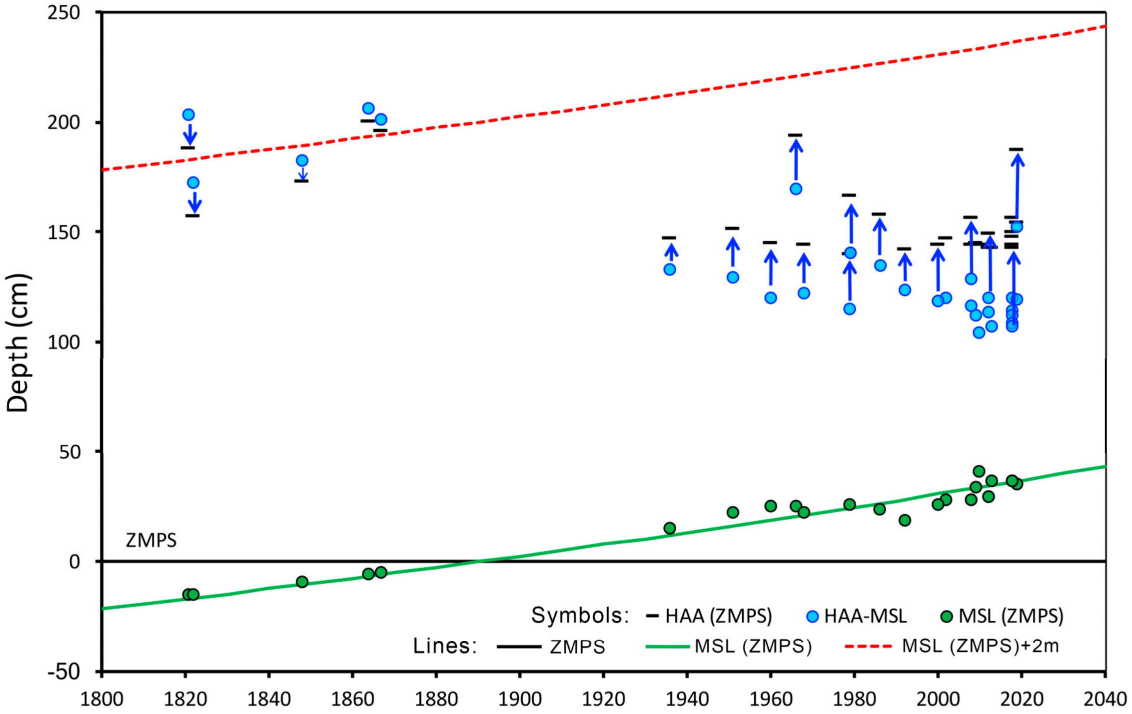


Figure 6. Sea level and AA over the last two centuries. Level marks '-': level reached by AA in the ZMPS frame. This level corresponds to the height indicated on commemorative plaques, also counted from the ZMPS. Blue dots: the excess of water that had risen above the MSL of the current year. Green dots: mean sea level for the year, referring to the ZMPS. Continuous green line: curve interpolating the tidal series of Venice. Red dashed line: line parallel to the green curve, raised by 200 cm, to indicate the depth that the AA of the 19th century would have today if the same conditions were repeated. Horizontal black line: the zero level of the ZMPS frame. Blue arrows help to understand the connection between blue dots and the related level marks.

Figure 6 shows that in the 19th century, the AA reached exceptionally high extreme values. It is also evident that the actual levels reached by the waters on the walls (referring to the ZMPS baseline) differ from the actual rise each time in the waters above sea level (referring to the green dots), and that the difference between these two values changes over time with SLR and LLS. It follows that before 1897 we have $HAA_{ZMPS} < EW_{ZMPS}$; in 1897, $HAA_{ZMPS} = EW_{ZMPS}$; and in the period after 1897, $HAA_{ZMPS} > EW_{ZMPS}$. This difference becomes increasingly accentuated as the relative MSL increases. If the same high water conditions of the 19th century were to occur once again, they would move along the red dashed line and would have a much greater impact than in the past.

The climatology of cyclonic activity throughout the Mediterranean region is well-known over the most recent decades [1,2,63–66]. Compared to the high level of cloud with the most extreme depths of the 19th century, as represented in Figure 6, one might form the impression that the trend of Mediterranean cyclones and associated AA episodes is decreasing, and that we can look to the future optimistically. However, this perception is false, as one can recognize by looking at a longer time scale [7] or analyzing the most severe events of the recent past [67–69].

The severity ratings of the most extreme AA are not the same in the different frames. This becomes clear when comparing the values in Table 2. The first column is the severity rating of the deepest AA of the last 200 years, starting from the most exceptional surge. The next two columns (i.e., nos. 2 and 3) are related to the ZMPS system, while the last two (i.e., nos. 4 and 5) relate to the MSL system. The years in which named storm surges occurred are reported in columns 2 and 4. Column 2 reports the years related to the HAA-ZMPS flooding depths (column 3) measured (or calculated) in the ZMPS frame. Column 3 reproduces the observed HAA-ZMPS levels that the flood water reached on walls during each surge, without considering any subsequent SLR or LLS. The land is perceived to be stable and the sea level variable. The reported values are representative of the modern style, as well as of the marks of commemorative plaques, e.g., the marks '**-**' in Figure 6. It must be specified that the AA events after 1871 were directly recorded with the ZMPS style, so the values reported in column 3 are the original, untouched values. On the other hand, the AA events before 1871 were measured with the CM style, and they have been transformed into ZMPS using Equations (1), (3), and (6). Column 4 reports the years of HAA-MSL flooding depths (column 5) measured (or calculated) above the MSL of the current year. Column 5 reproduces the peaks of storm surges above the MSL of that year. This column is representative of the severity reached by each storm surge in combination with other synergic factors, and it is independent of SLR or LLS. The sea level is perceived to be stable and the land variable. The reported values are representative of the blue dots in Figure 6. In column 5, the AA events before 1871 have been transformed from CM to MSL with Equation (3). For the AA events after 1871, column 5 reports the difference between the peak value (HAA) and the MSL of that year.

Table 2. List of the most extreme levels of AA (HAA) to have occurred in the past two centuries, ordered by severity. They are indicated with the year of occurrence and the HAA depths measured (or calculated) with the ZMPS (land-linked system, columns 2 and 3) and MSL (sea-linked system, columns 4 and 5). The famous AA of 1966 is highlighted in bold. The background of the AA of the 19th century is blue, the 20th century white, and the 21st century yellow.

Rating	Year ZMPS	HAA-ZMPS (cm)	Year MSL	HAA-MSL (cm)
1	1864	200	1864	206
2	1867	196	1821	203
3	**1966**	**194**	1867	201
4	1821	188	1848	182
5	2019	187	1822	172
6	1848	173	**1966**	**169**
7	1979	166	2019	152
8	1986	158	1979	141
9	1822	157	1986	135
10	2008	156	1936	133
11	2018	156	1859	130
12	1951	151	1951	129
13	2012	149	2008	128
14	1936	147	1992	124
15	2002	147	1968	122
16	1960	145	2018	120
17	2009	145	1960	120
18	1968	144	2012	120
19	2000	144	2002	119
20	2010	144	2000	118
21	2013	143	2009	112
22	1992	142	2013	107

Table 2 includes the top 22 AA events according to the ZMPS and the same for the MSL. Somebody might ask why 22, and not more or less? The choice is irrelevant, but there are some good reasons for stopping at the selected ranking level: (i) in the 19th century, only the most severe AA events were reported, disregarding normal ones, and for homogeneity, we must assume the same criterion for the subsequent period; (ii) beyond that threshold, there was more than one AA with the same depth, which made the ranking confusing; (iii) the aim of the table is to explain the difference between the two frames, not to a produce dataset; and (iv) every choice is subjective. It would have been equally possible to stop a little earlier or a little later.

A comparison of the columns highlights the following differences. The severity rating changes with the definition and the related reference frame. Departures between the two frames may reach several tens of centimeters. It should be noted that, before 1871, the values obtained from the MSL frame (column 5) are greater than those with the ZMPS (column 3), while in the years following 1871, the situation is reversed.

Table 2 provides other key information on the distribution over time, better shown in Figure 7. The frequency of the 22 most severe AA events does not significantly change when using either the ZMPS or the MLS reference. In the 19th century, the AA events are less frequent than in the next two centuries. The number of AA events in the first quarter of the 21st century equals the number of AA events over the whole of the 20th century, showing that this frequency is impressively increasing with the sea level rise.

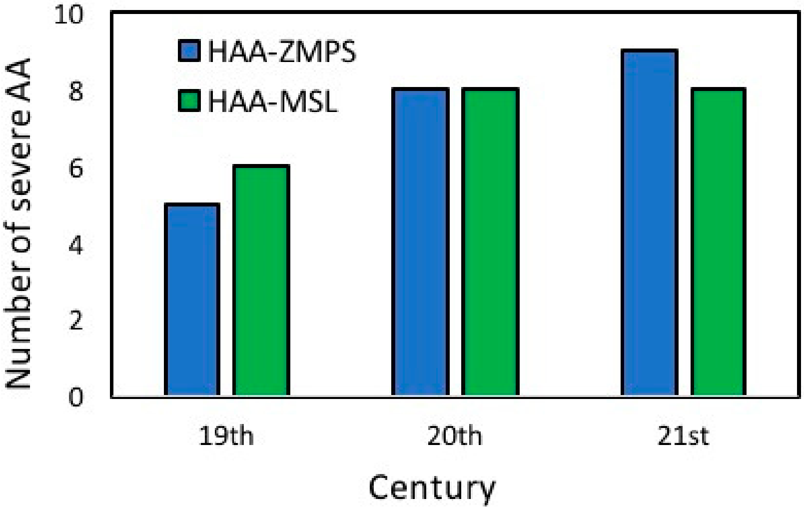


Figure 7. Overview of the frequency of the most severe AA instances to have occurred in the 19th and 20th centuries and the first quarter of the 21st century.

5.2. *Perception*

Let us consider a hypothetical case: There is a wall with a memorial plaque recording the most severe historical floods, and we want to find those that exceeded the recent one in 2019. If we consider the ZMPS frame, i.e., columns 2 and 3, 2019 is in fifth position. The top mark is 1864, followed closely by 1867 and 1966, and then, at short distance, by 1821 and 2019, with all these marks being included in the top 13 cm. On the other hand, if we consider the MSL, i.e., columns 4 and 5, then 2019 is in seventh position. The top mark is 1864, followed by 1821, 1867, 1848, 1822, 1966, and, finally, 2019, with all these marks being spread over the top 54 cm. In particular, the departure between the two deepest AA events in the modern tide gauge record, i.e., between 1966 and 2019, is 7 cm in the ZMPS, while the departure between them is 17 cm when they are referred to the sea level using the CM or MSL frame.

The comparison between the marine- and the land-linked reference systems shows that, in a frame related to the sea level, the HAA depth reached by an AA is represented by the exceptional EW contribution of the sea rise (either above CM or MSL, depending on the choice), i.e.,

$$\mathrm{HAA}_{\mathrm{MSL}} = \mathrm{EW}_{\mathrm{MSL}} \tag{7}$$

while in the ZMPS reference, it is given by the sum

$$\mathrm{HAA}_{\mathrm{ZMPS}} = \mathrm{MSL} + \mathrm{EW}_{\mathrm{ZMPS}} \tag{8}$$

Therefore, HAA_{ZMPS}, in referring to the MSL, is affected by SLR and LLS and will increase with them.

As another hypothetical case, suppose there are two identical AA peaks with the same EW elevation (either EW_{CM} or EW_{ZMPS}) above sea level, occurring at two years t_{yr1} and t_{yr2}. In the marine MSL frame, they will continue to have the same EW and the same severity, while in the ZMPS frame, they will have different HAA_{ZMPS} levels, which depart by

$$\Delta HAA_{ZMPS} = \Delta MSL = MSL_2 - MSL_1 = SLRR\ \Delta t_{yr} \tag{9}$$

where SLRR is the annual rise rate of the MSL, and Δt_{yr} is the number of years elapsed from t_{yr1} to t_{yr2}.

5.3. Commemorative Plaques: Perception and Reality

Today, the HAA_{ZMPS} depth reached by an AA event is measured according to the ZMPS, which is physically linked to local land and buildings. Venice has suffered many flood waters, but it has relatively few commemorative plaques. The most important commemorative plaque is located in Cà Farsetti (Figure 8a) and shows the marks of 1916, 1936, 1951, and 1966. The HAA_{ZMPS} levels of the marks are 26 cm, 35 cm, 39 cm, and 77 cm, respectively, which agree with those in Table 2, column 3, if one considers that the walking level of the street is 114 cm above the ZMPS (Figure 8b, altimetry performed in 2011 by Insula, Venice) and that the error band within ±2 cm is partially explained by the uneven paving. Therefore, the deepest depth reached by waters in 1966, i.e., 194 cm, is 74 cm above the street pavement.

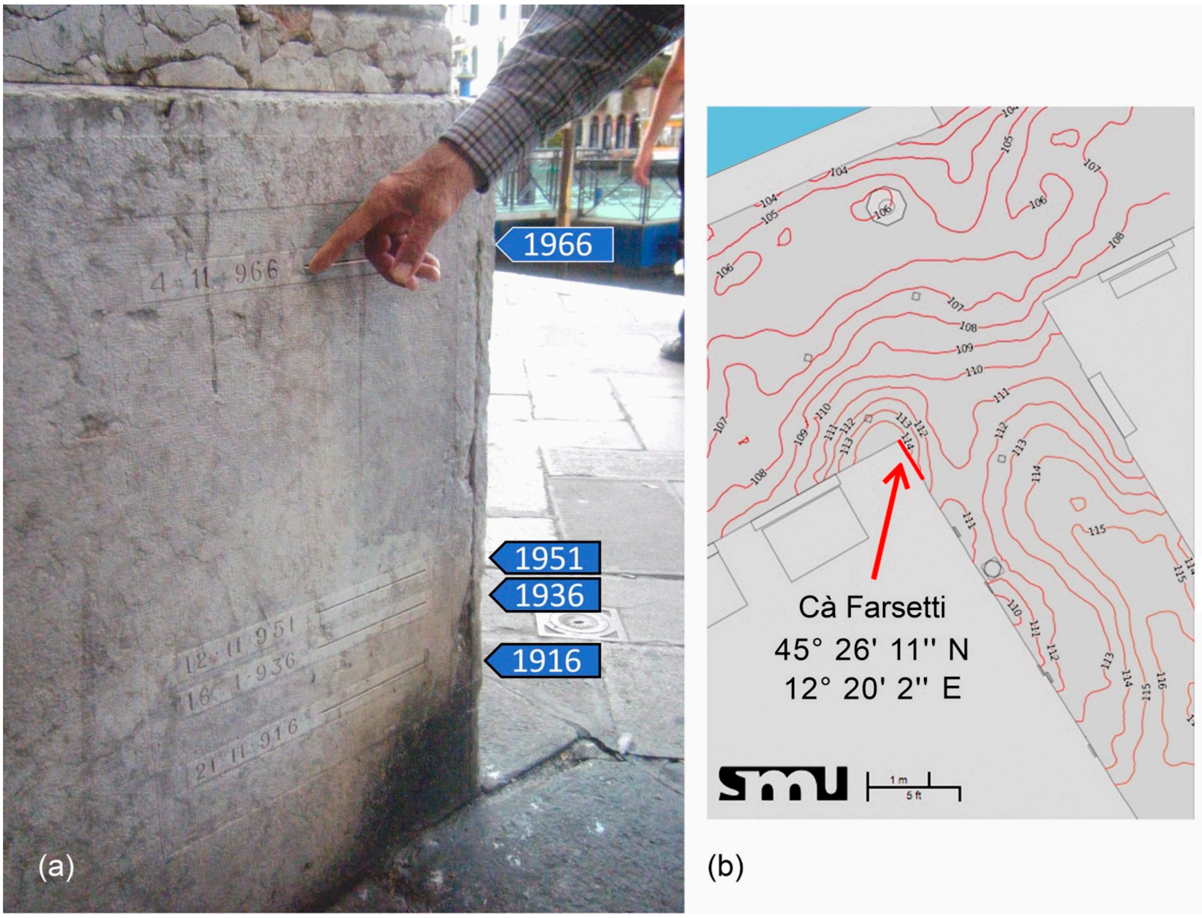


Figure 8. (**a**) Commemorative plaque on the Cà Farsetti palace, with the levels reached by flood waters in 1966, 1951, 1936 and 1916. (Photo: Luigi Cavaleri.) (**b**) Altimetry of the site: 114 cm ZMPS. The red arrow shows the position of the plaque. (Map and information source: SMU, Insula spa, Venice).

By marking walls with the most extreme depths reached by the historic AA events, citizens are informed about the past and also the highest levels that may be reached in the future. However, there is a difference between perception and reality, and the perception is false because of the SLR and LLS. The ZMPS system reflects the perceptions of inhabitants, based on these marks of the levels reached by water on buildings, where water has deteriorated everything below this level. However, the longer the time Δt_{yr} that elapsed between events, the wider the difference and the greater the inconsistency between marks, as demonstrated by Equation (9). This situation may generate confusion and false perceptions.

For instance, a plaque is located in a street named Salizada dei Spechieri, civic no. 4886, which reports the depth reached on 15 January 1867 (Figure 9). From contemporary sources [4,19,53,54,70,71], including the newspapers cited in Figure 5d,e, we know that the flood reached 159 cm above CM, which corresponds to 196 cm ZMPS (i.e., 2 cm higher than the famous AA of 1966, see Table 2). Today, the plaque lies on the pavement of the street, which is 143 cm above ZMPS (Figure 9c, altimetry performed in 2011, by Insula). The level mark is 5 cm above the walking level, i.e., 148 cm ZMPS. As such, the present-day position is 48 cm lower than would be correct, with the true position indicated by the empty rectangle in Figure 9a. It should be noted that the position of the crack on the plaque fits with the failure of the wall at the expected position.

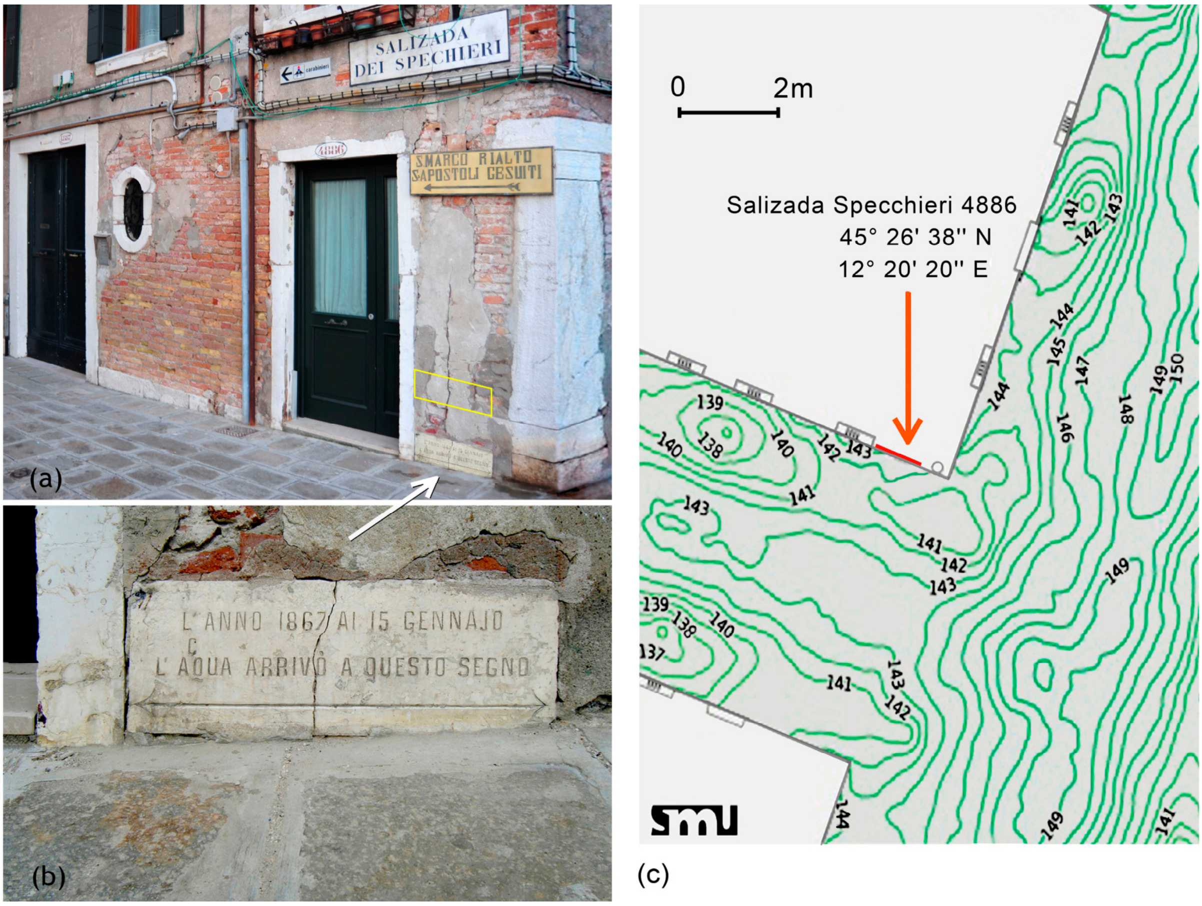


Figure 9. (**a**) General view of the building on the corner at the end of the Salizada dei Spechieri street, with the plaque commemorating the Acqua Alta of 15 January 1867. The plaque lies at the foot of the wall (white arrow). The expected original position is some ½ m higher, as indicated by the rectangle with yellow edges. (Photo: Massimo Bertacchi [72].) (**b**) Detail of the plaque. Text: 'In the year 1867, 15 January, the water reached this mark'. (Photo: Luigi Cavaleri.) (**c**) Altimetry of the site: 143 cm ZMPS. The red arrow shows the position of the plaque. (Map and information source: SMU, Insula spa, Venice.)

We suppose that, originally, the plaque was correctly positioned on the wall; it was later detached for maintenance works to the building, temporarily placed on the floor, at the foot of the wall, and, finally, fixed in that position at the end of works. In this way, the plaque changed its function: from a testimony of history to an edging stone for the protective profile at the foot of the building.

6. Conclusions

From the historic point of view, the old CM frame was used first and then the ZMPS. This does not necessarily mean that the ZMPS is an evolution or that it is better. Both the CM and ZMPS frames are relative systems, each of them linked to a mobile reference, and the two frames are in relative motion. Each follows a different physical point of view and has some pros as well as some cons, depending on the use and aims, i.e., in what light the AA is considered.

If one is concerned with the interactions between the atmospheric forcing and the sea, and wants to know the excess water dragged by a storm surge above the sea level, or assess a rating of the most severe storm surges, then the most convenient frame is linked to the MSL, which derives from the old CM frame.

However, if one wants to know the flooding depth reached above the urban streets, and to relate it to the damage to citizens, buildings, and goods, then the ZMPS frame is preferable. This frame is representative of the level really reached by water on walls, as it is perceived by people.

The IGM Genova 1942 frame would be better, because it is not affected by the local subsidence of Venice, but it is difficult to change the traditional use and the related scientific literature.

We have seen that, in the 19th century, when the MSL was below the ZMPS, their difference was negative, and the depths of AA events expressed in terms of the ZMPS were underestimated. Vice versa, after 1871, the difference became positive, and the overestimation relative to the flooding depth increased with the MSL. If, today, or in the future, the same conditions that caused the floods of the 19th century were to be repeated, they would produce much higher water levels in the city, causing a much bigger impact.

In the 19th century, the floods were deeper than in the 20th and 21st centuries. This fact does not constitute an index of a decreasing trend, which could suggest lowering the alert level, but is a fortuitous consequence of the 19th century having been characterized by more severe cyclogenetic activity. This is not surprising, because AA events are generated by Mediterranean cyclones, typically in the cold season, fed by the sensible and latent heat released by sea water, and driven by the contrast between water and air temperatures. This contrast can increase either with warmer sea waters (as one might expect for the future) or with colder winds (as there might have been in the 19th century).

Commemorative plaques engraved with the past flooding levels are very valuable from the points of view of history, documentation, and culture. However, even when they have not been removed from their original position, they give a false, underestimated perception of the most extreme events that occurred in the past and could be repeated in the future. This false perception derives from the fact that we look at them without considering the temporal dates, and the sea level has risen in the meantime, while the land had sunk, altering the situation. For this reason, extreme historic flood levels may be found at short distance from more modest flood levels that have occurred in recent times.

Satellite altimetry offers the most recent absolute frame. This information follows an advanced logic, with absolute readings, but the recent satellite dataset is too short to be compared with long time series. The absolute trend of SLR of the Adriatic Sea has been assessed for the last three decades, i.e., from 1992 to 2022, and the results (i.e., +2.1 ± 0.4 mm/year) are in excellent agreement with the tide gauge data (i.e., +1.95 ± 0.5 mm/year). We have seen that the records of the tide gauges are based on relative scales affected by a number of problems; however, tide gauges provide continuous readings over time, have long-term records, and thus remain a fundamental instrument, even if their output is expressed in a relative scale.

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Data Availability Statement: The data before 1871 were published in [4,7]. The data from 1872 are downloadable from the websites of the Municipality of Venice, Tide Forecasting and Reporting Centre https://www.comune.venezia.it/it/content/archivio-storico-livello-marea-venezia-1 and the Italian Institute for Environmental Protection and Research (ISPRA) https://www.venezia.isprambiente.it. The urban altimetry, of the Insula's Urban Maintenance System (SMU), is based on a three-dimensional laser scanner survey carried out in 2011. Public access is at https://smu.insula.it/. All websites were accessed on 1 March 2024.

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Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this paper:

Δ	mathematical symbol to indicate a difference between two terms as specified in the text
ΔH	additional wetting level reached by high tides and waves
Δ(IGM–ZMPS)	difference between values measured with the frames IGM Genova 1942 and ZMPS
Δt_{yr}	number of years elapsed between two years, t_{yr1} and t_{yr2}
$\sum$	mathematical symbol to indicate a sum of terms as specified in the text
AA	Acqua Alta (the local name for the flood water)
CM	Common Marine Mark
EW	excess water generated by a surge
HAA	depth reached by the AA
IGM	Istituto Geografico Militare
LLS	local land subsidence
MSL	mean sea level
SLR	sea level rise
SLRR	annual rise rate of the MSL
ZMPS	Zero Mareografico di Punta Salute (zero tide level of Punta Salute)

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