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Four centuries of documentary sources concerning the sea level rise in Venice

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Abstract
Four centuries of written documentary sources concerning sea level rise (SLR) in Venice are analysed to complete the study of potential proxies. This literature has been useful to advance knowledge in history of science and to recover scientific data. Several case studies have been found and discussed, but only two had complete information to reach quantitative sea level values. The first one was reported by Manfredi (1732) and is representative of the 1500–1730 period. The second was by Zendrini (1821) who gave a benchmark in 1810. The results are compared with the multiproxy SLR reconstruction for the 1350–2016 period (Camuffo et al. 2017). Manfredi constitutes an independent verification of this multiproxy series.

Keywords Sea level rise · Documentary data · Proxy data · Venice

1 Introduction

The coast of the northern Adriatic Sea is affected by sea level rise (SLR), a combined effect of eustatism and local land subsidence (LLS). The UNESCO coastal cities and their cultural heritage faced, and will continue to face, this challenge (Reimann et al. 2018).

In Venice, the first tide gauge was installed in 1871 at the Punta della Salute, in front of S. Marco Square, and proxies are necessary to document the previous time. The first proxy we analysed was the algae level reported on the paintings by Canaletto and Bellotto (eighteenth century) (Camuffo and Sturaro 2003). The situation in 1571 was identified from the water stair of the Coccina Palace represented in a painting by Veronese (Camuffo 2010). The second proxy was the submersion of the water stairs of the palaces facing the Grand Canal, built from 1350 to 1800. This

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required measuring the underwater depth of the first step (Camuffo et al. 2017). This paper is concerned with a thorough analysis of a third proxy, i.e. the written documentary sources from the sixteenth to the nineteenth century.

Until the sixteenth century, the Venetians missed a precise perception that the Lagoon had serious problems and that relative sea level was rising. It was believed that in the Lagoon, the water level could not change because the Lagoon was connected to the Adriatic and the Mediterranean Seas, and the Ocean, and that the global balance of the marine and oceanic waters, due to evaporation and precipitation, could not change. Initially, nobody suspected that the land could subside. Historically, the discovery in Venice and the hinterland of underground remains (e.g. ancient floors and pottery related to the Roman period), or old churches having a second, deeper floor underneath, was interpreted as an indisputable evidence that the sea level was rising. The Venetians thought that the Lagoon risked to be transformed into salt marshes, reed beds and mud flats, with negative consequences on sailing, fishing and environmental health. They also considered the need of continuous works of maintenance, protection and the diversion of the rivers that flowed into the Lagoon. In 1501, the Water Magistrate was founded to control the legislation, the hydraulic works and the sedimentation of the turbid water that rivers transported into the Lagoon. In 1732, when the Venetians were obliged to raise the pavement of San Marco Square because it was too frequently flooded, they had a direct perception.

This challenging situation was documented. The first aim of this paper is to analyse four centuries of written sources about the sea level in Venice, interpret them and assess the reliability of the quantitative observations.

The second aim is to compare the results obtained from the written sources with the best-fit of the multiproxy series in Venice (Camuffo et al. 2017).

2 Analysis of the documentary sources

2.1 Introductory notes

Historical documents A thorough analysis has been made of the manuscripts and printed sources, written in Latin, Old Venetian and Italian, that document or discuss SLR in Venice from the sixteenth to the nineteenth centuries. The key results are reported by century. Links to the digitized historical documents are provided in Table 1.

Units The metric system was created in 1789, and the International System of Units was established in 1860s. Previously, the basic unit was 1 ft that was divided in 12 parts called inches or ounces. Every city-state had a particular value that was carved in the stone of the municipal building. Units were not specified because it was implicitly assumed that measurements were made in local feet. In the Venice Republic, the unit was 1 ft = 34.76 cm; 1 in. = 2.897 cm; in the region around Bologna, 1 ft = 38.0098 cm; 1 *oz* = 3.1677 cm.

Historical sea level reference Before the instrumental period, green algae constituted a ubiquitous marker of the current sea level. This was known to all sea peoples. In Venice, the green algae belt was used as official reference of sea level (Rusconi 1983), and when it was suspected that it could change, it was engraved on stone benchmarks. One of the earliest

Table 1 Links to the Digital Library

Reference	Digital Text (Google Books) (Accessed 2 August 2021)
Campilanzi (1840)	https://www.google.it/books/edition/Annali_Delle_Scienze_Del_Regno_Lombardo/u-BaAAAAcAAJ?hl=it&gbpv=1&dq=1840+Sulla+corrispondenza+dei+cangiamenti+di+livello+del+mare+osservat&pg=PA326&printsec=frontcover
Castelli (1641)	https://www.google.it/books/edition/Raccolta_d_autori_che_trattano_del_moto/9zMly_F6-VIC?hl=it&gbpv=1&dq=Raccolta+d%E2%80%99Autori+che+trattano+del+moto+dell%E2%80%99Acque,+Vol.1&pg=PA72&printsec=frontcover
Castelli (1642)	https://www.google.it/books/edition/Raccolta_d_autori_che_trattano_del_moto/9zMly_F6-VIC?hl=it&gbpv=1&dq=Raccolta+d%E2%80%99Autori+che+trattano+del+moto+dell%E2%80%99Acque,+Vol.1&pg=PA72&printsec=frontcover
Celsius (1743)	https://www.google.it/books/edition/Der_K%C3%B6nigl_Schwedischen_Akademie_der_Wi/63NlAAAAcAAJ?hl=it&gbpv=1&dq=Der+Konigl+Schwedischen+akademie+der+wissenschaften+Kastner+funfter+band&pg=PP5&printsec=frontcover
Cornaro and Sabbadino (1551)	http://asa.archiviostudiadriatici.it/islandora/object/libria:41949/datastream/PDF/content/libria_41949.pdf
Filiasi (1797)	https://www.google.it/books/edition/Memorie_storiche_de_Veneti_primi_e_secon/aeCO48k3Wh4C?hl=it&gbpv=1&dq=Filiasi++Memorie+storiche+Veneti+primi+e+secondi&pg=PA1&printsec=frontcover
Filiasi (1811–14)	https://www.google.it/books/edition/Memorie_storiche_de_Veneti_primi_e_secon/NoS-jvSptkMC?hl=it&gbpv=1&dq=Filiasi++Memorie+storiche+Veneti+primi+e+secondi&printsec=frontcover
Filiasi (1817)	https://www.google.it/books/edition/Riflessioni_sopra_i_fiumi_e_le_lagune/R59RAAAAcAAJ?hl=it&gbpv=1&dq=Filiasi++Memorie+storiche+Veneti+primi+e+secondi&pg=PA4&printsec=frontcover
Gallicciolli (1795)	https://www.google.it/books/edition/Delle_Memorie_Venete_Antiche_Profane_Ed/LGg5AAAAcAAJ?hl=it&gbpv=1&dq=Filiasi++Memorie+storiche+Veneti+primi+e+secondi&pg=PA38&printsec=frontcover
Hartsoecker (1706)	https://www.google.it/books/edition/Conjectures_physiques_Par_Nicolas_Hartso/Ze1-qcSgf1oC?hl=it&gbpv=1&dq=Hartsoecker+Conjectures+physiques.&pg=PA190&printsec=frontcover
Kant (1802)	https://www.google.it/books/edition/Physische_Geographie/iNtQAAAAcAAJ?hl=it&gbpv=1&dq=Kant++Physische+Geographie&pg=PA17&printsec=frontcover
Kant (1808)	https://www.google.it/books/edition/Geografia_fisica_di_Emanuele_Kant_tradot/ZTw5OKEX72MC?hl=it&gbpv=1&dq=Kant++Physische+Geographie&pg=PA33&printsec=frontcover
Leonardo	Not available
Linnaeus (1744)	https://www.google.it/books/edition/Caroli_Linnaei_prof_med_et_botanic_Orati/y0ZnAAAAcAAJ?hl=it&gbpv=1&dq=Linnaeus++Oratio+de+Telluris+habitabilis+incremento&printsec=frontcover
Manfredi (1732)	https://www.google.it/books/edition/Nuova_Raccolta_d_autori_che_trattano_del/gspWAAAAcAAJ?hl=it&gbpv=1&dq=Manfredi+Sopra+l%E2%80%99alzarsi+che+fa+di+continuo+la+superficie+del+mare&pg=PP9&printsec=frontcover
Paleocapa (1844)	https://www.google.it/books/edition/Considerazioni_sulla_costituzione_geolog/2pZmAAAAcAAJ?hl=it&gbpv=1&dq=Paleocapa+P+(1844)+Considerazioni+sulla+costituzione+geologica+del+bacino+di+Venezia&pg=PP5&printsec=frontcover
Paoli (1838)	https://www.google.it/books/edition/Bibliografia_italiana_Nouva_ser_ann/5zMGAAAAQAAJ?hl=it&gbpv=1&dq=Paoli+D+(1838)+Del+sollevamento+e+dell%E2%80%99avvallamento+di+alcuni+terreni&pg=RA1-PA228&printsec=frontcover
Pini (1793)	https://www.google.it/books/edition/Opuscoli_scelti_sulle_scienze_e_sulle_ar/P-4WAAAAYAAJ?hl=it&gbpv=1&dq=Pini+E+(1793)+Sulle+rivoluzioni+del+

Table 1 (continued)

Reference	**Digital Text (Google Books)** (Accessed 2 August 2021)
	Globo+Terrestre+provenienti+dall%E2%80%99azione+delle+acque&pg=RA1-PA9&printsec=frontcover
Planci (1739)	https://www.google.it/books/edition/Jani_Planci_Ariminensis_De_conchis_minus/nO9VDBCPU94C?hl=it&gbpv=1&dq=Specimen+aestus+reciproci+maris+superi+ad+littus+portumque+Arimini&pg=PA85&printsec=frontcover
Poleni (1767)	https://books.google.it/books?id=4QZZAAAAcAAJ&printsec=frontcover&hl=it&source=gbs_ge_summary_r&cad=0#v=onepage&q=poleni&f=false
Ponti (1888)	https://www.google.it/books/edition/Giornale_del_Genio_Civile_Parte_non_uffi/beLY60OuSPMC?hl=it&gbpv=1&dq=Ponti+Delle+livellazioni+di+precisione&pg=PA3&printsec=frontcover
Sabbadino (1543 ca)	Not available
Sabbadino (1557)	Not available
Sansovino (1604)	https://www.google.it/books/edition/Venetia_citt%C3%A0_nobilissima_et_singolare/fmFTZAPj7tYC?hl=it&gbpv=1&dq=Sansovino+F+(1604)+Venetia+citt%C3%A0+nobilissima+et+singolare&pg=RA5-PA123&printsec=frontcover
Temanza (1761)	https://www.google.it/books/edition/Dissertazione_sopra_l_antichissimo_terri/LB9PAAAAcAAJ?hl=it&gbpv=1&dq=Temanza+T+(1761)+Dissertazione+sopra+l%27antichissimo+territorio+di+Sant%27Ilario&pg=PR37&printsec=frontcover
Tentori (1792)	https://www.google.it/books/edition/Della_legislazione_Veneziana_sulla_prese/2SFWAAAAcAAJ?hl=it&gbpv=1&dq=Tentori+C+(1792)+della+legislazione+Veneziana+sulla+preservazione+della+laguna,&pg=PA51&printsec=frontcover
Zendrini A (1802)	https://www.google.it/books/edition/Giornale_dell_Italiana_letteratura/BhBSAAAAcAAJ?hl=it&gbpv=1&dq=Zendrini+A+(1802)+Memoria+sull%E2%80%99alzamento+del+livello+del+mare.&pg=PA31&printsec=frontcover
Zendrini A (1818)	https://www.google.it/books/edition/Lettera_all_autore_dell_opera_intitolata/rFBmAAAAcAAJ?hl=it&gbpv=1&dq=Lettera+all%27autore+dell%27opera+intitolata+Rifessioni+sopra+i+fiumi+e+le+lagune&pg=PA34&printsec=frontcover
Zendrini A (1821)	https://www.google.it/books/edition/Memorie_dell_Imperiale_Regio_Istituto_de/SYztT-H9WTUC?hl=it&gbpv=1&dq=Nuove+ricerche+sull%27alzamento+del+livello+del+mare&pg=RA1-PA155&printsec=frontcover
Zendrini A (1845)	https://www.google.it/books/edition/Memorie_del_Reale_veneto_istituto_di_sci/BT7mAAAAMAAJ?hl=it&gbpv=1&dq=zendrini+Esame+di+alcuni+fatti+geologici&pg=PA213&printsec=frontcover
Zendrini B (1741)	https://www.google.it/books/edition/Leggi_e_fenomeni_regolazioni_ed_usi_dell/8WvRcXfDfjgC?hl=it&gbpv=1&dq=Zendrini+B+(1741)+Leggi+e+fenomeni,+regolazione+ed+usi+delle+acque+correnti.&pg=PA163&printsec=frontcover
Zendrini B (1811)	https://www.google.it/books/edition/Memorie_storiche_dello_stato_antico_e_mo/_0ZJAAAAcAAJ?hl=it&gbpv=1&dq=Zendrini+B+(1811)+Memorie+storiche+dello+stato+antico+e+moderno+delle+lagune+di+Venezia&pg=PA368&printsec=frontcover
Zendrini and Manfredi (1731)	https://www.google.it/books/edition/Relazione_per_la_diversione_de_fiumi_Ron/cBYV1t7A-nMC?hl=it&gbpv=1&dq=Relazione+per+la+diversione+de%E2%80%99+fiumi+Ronco+e+Montone+e+sopra+il+generale+regolamento+delle+acque&pg=PR5&printsec=frontcover

references was a sea surge in 1283–1284 described by an early chronicle: “there was very high water: it rose more than a step above the ‘*comune*’ causing a lot of damage and poisoning all wells in Venice” (Enzi and Camuffo 1995). Green algae live on quays and buildings, in the intertidal belt characterized by tidal cycles where algae find an alternation of solar radiation needed for the chlorophyll and sea water needed for hydration. The top of green algae is evident and widespread in all canals, and the Venice Republic called it *Comune Marino* (CM, for "common-sea-level"). CM was assumed to be the base level for measuring elevation and depth for private and public works, e.g. quays, buildings and bridges. It was traditionally believed that CM was the average level of the high tides (Rusconi 1983). However, direct measurements of CM and sea level have shown that CM corresponds to the periodic wetting due to the combined effect of high tides and small waves. In the eighteenth century, CM was 42 ± 2 cm above the mean sea level, of which 30 ± 2 cm were actually due to tide, and the additional 12 ± 1 cm were due to wind waves and local row-boat traffic; nowadays the wave height has increased by 5 ± 1 cm as a result of motor boat traffic (Camuffo et al. 2017).

Local land subsidence For the interpretation of the historical sources, it is necessary to specify that in Venice, the local land subsidence contributes to determine the relative SLR. Several studies have been made to determine LLS, using different approaches and methods, making reference to different time scales, and sampling in different locations, either in Venice, the Lagoon, or along the coast, near to or far from Venice (for details and references, see ESM and cited literature). The LLS values reported in the literature lie in the range between 0.9 and 1.4 mm yr^{-1}, with median 1.15 ± 0.25 mm yr^{-1}. In their models, Doglioni (1993), Carminati et al. (2003, 2005) and Lionello et al. (2020) estimated that the natural subsidence due to enduring long-term geological trends has been and will continue to be around 1 mm yr^{-1} and assumed the round number approximation. For the comprehension of this paper, an exact value is not needed, and we can follow Tsimplis et al. (2011): "the basic assumption is that past local vertical movement was at a steady rate over hundreds to thousands of years, and that is continuing now at the same rate". In this case, the assumption may be limited to some hundreds of years. In addition, it is necessary to clarify that, during the period covered by this study, the LLS rates in Venice and Ravenna were different (in Ravenna was unknown), making not comparable their SLR rates.

Local or foreign scientists In this section, the persons active in the Venetian Republic, or appointed by it, are highlighted with an asterisk*. These persons had direct contact with the situation and the documents.

2.2 The documentary sources by century

2.2.1 Sixteenth century

In this period, a fundamental debate started and continued for two centuries. The key issues were as follows: (i) the awareness that sea level was rising, (ii) to recognize the cause and mechanism and (iii) to adopt the most efficient way to stop SLR. The discussion was focused on the risks arising from rivers, i.e. if turbid rivers transport sand, mud and gravel, and this matter settles on the bottom, the sea level will be raised or not? Sabbadino stressed the issue that silting will reduce the Lagoon depth over time; Cornaro stressed the risk that a coastal silting may reduce the extension and the volume of the Lagoon over time. Although this was never specified, both claims had the same underlying assumption: the Lagoon was considered an almost closed system because it was separated from the sea by a stretch of land with small interruptions. This stretch could be considered a series of six consecutive islands or a tongue of land crossed by seven interruptions that constituted seven small connections between the Lagoon and the sea. However, these connections were small, and the water exchanges were considered limited or even negligible. The everyday experience showed that inside the Lagoon, especially in shallow waters and marshes, the tidal range was reduced and the phase delayed in comparison to the open sea, suggesting a certain independency. The Venetians noted that silting increased over time. They believed that, if the system was really open, the solid transport would be dispersed in the sea, and internal silting should not occur. Their conclusion was that the Lagoon was an almost closed system, and silting will raise the level. As a prudential measure, the Venetians started to divert rivers out of the Lagoon.

The public discussion started when Cristoforo Sabbadino*, a leading scientist, with the official charge of Foremost Engineer of Waters (equivalent to Minister of Hydraulic Works of the Venice Republic) presented some dramatic and contradictory examples. These were based on the visual evidence but were uncertain because they missed a precise depth and/or a precise time reference. Sabbadino (1543ca) wrote that in Venice, near the church of S Agnese, Mr. Arcangelo Eremitano was digging a well for freshwater, and at the depth of around 5 ft (i.e. 174 cm), he found an ancient brickwork floor, typically an early technique, that he estimated 500 years old. This (uncertain) dating implied a secular rate of 1 ft per century (i.e. 34.7 cm century^{-1}). This interpretation conditioned most of the subsequent literature. After having analysed other case studies, including the crypt of S Marco Basilica, Sabbadino (1543ca) changed rate, i.e. 3–4 ft over the past 11 centuries (i.e. 9.4–12.6 cm century^{-1} = 11 ± 1.6 cm century^{-1}).

The polymath genius Leonardo da Vinci (1452–1519) made clear that, when a turbid river flows into marshes, it will slow down and deposit the material in suspension, raising the bottom. Following this advice, Sabbadino (Cornaro and Sabbadino 1551; Sabbadino 1557) considered that rivers erode inlands and deposit into the Lagoon. Sabbadino stressed the importance of diverting all rivers with turbid water (i.e. Adige, Bacchiglione, Brenta, Sile and Piave) out of the Lagoon. This was realized in the following centuries. The second suggestion was to improve the exchanges with the sea. It was believed that the uplift of the bottom would have raised waters, including the tidal level.

Alvise Cornaro* was a nobleman and patron of arts, involved in hydraulic works and reclamation of the Lagoon marshes. He disagreed with Sabbadino and stressed the importance of taking care of the Lagoon borders because if the Lagoon volume would have been reduced, the water transported by the rivers would have raised the Lagoon level (Cornaro and Sabbadino 1551). Of course, he neglected that the Lagoon was open, in connection with the sea. He was a supporter of the rate 1 ft per century.

2.2.2 Seventeenth century

Francesco Sansovino* (1604), a leading humanist, wrote a monumental history of Venice in 14 books. In the first book, he described the geographic position and the surrounding territory. In antiquity, there was a deep Lagoon with seven rivers flowing in it. The Lagoon received freshwater from the rivers and saltwater from seven gates on the natural barrier that separated the Lagoon from the sea. This situation allowed free water exchanges and normal tidal cycles. No mention was made of long-term trends in the sea level or about the material that could deposit on the Lagoon bottom.

Father Benedetto Castelli*, a Galileo's pupil and friend, inventor of the rain gauge, expert in hydraulics and professor at the University of Rome, was appointed to analyse the problems of the Lagoon and gave his advice (Castelli 1641). The first issue was that, at low tides, marshes and mud flats exposed an area too large to the sun, which overheated the surface, the air and the shallow waters, rotting the air, favouring mosquitos and being harmful for fish. The second issue concerned the silting of the ports located on the gates to the sea. He considered it crucial to identify the true cause: i.e. if the bottom was rising, then it was necessary to dig; if the water was sinking for shortage, it was necessary to add more water. He made this consideration because, in 1324, the Brenta River was diverted out of the Lagoon, greatly reducing the freshwater input. Following Leonard, Castelli thought that, near the river mouth, the sea exerts an opposite action, and in this contrast, the mud is deposited on the bottom. He believed that, after the Lagoon was deprived of the input of the Brenta River, the ports that were located at the gates between the Lagoon and the sea were silting for the changed hydraulic regime. He suggested to restore the previous equilibrium, but with clear waters. Later, Castelli (1642) discussed how to measure river flow and turbidity. After this advice, the Council of Venice stopped the works to divert the Sile and other four rivers. However, 40 years later, in 1683, after an outflow of the Sile, the Venice Republic decided to disregard this advice and continued to divert all rivers.

This century had two key issues. Sansovino made a realistic explanation of the Lagoon-sea exchanges. Castelli advised that diverting all rivers would have caused a new unpredictable equilibrium and related risks, and stopped the diversion works, at least temporarily.

2.2.3 Eighteenth century

At the beginning of the eighteenth century, Hartsoecker (1706), and later Manfredi (1732), made a global model, based on meteorological data and field observations, to evaluate the consequences of silting caused by the solid sediment transport in rivers. They assumed that the total mass of the marine and oceanic waters was constant and kept in a natural basin with fixed walls. They supposed that, if silting would raise the bottom of this basin, also the upper level of waters will be raised, and the waters will overflow invading the coastal areas and low lands. They calculated the global silting making two assumptions: (i) the total flow of all rivers equals the total depth of rain falling over the Earth, and (ii) the solid transport was evaluated by measuring the turbidity in some case study, supposed to be representative of all rivers. They assumed that all rivers of the world follow the same behaviour and that the solid matter will settle homogeneously over the floor of all seas and oceans. The two inputs to this global model, i.e. total precipitation and turbidity, were estimated in excess, and the authors obtained a dramatic scenario. This global scenario constituted the primary concern of the first half of the century, until Celsius and Linnaeus destroyed it, discovering that not all seas followed the same trend, but some of them were lowering. This revolutionary discovery was made in the 1740s, but it passed unobserved because it was written in Swedish. It required some decades to be disseminated and become popular.

The Dutch mathematician and physicist Nicolaas Hartsoecker (1706), the inventor of the microscope, returned to the basic idea that all the rivers of the world transport solid material that will settle on the seabed, raising the water level. To evaluate this mechanism, he sampled some turbid water of the Rhine River and found that the fraction of mud suspended in water was in the ratio 1:99. On this ground, he calculated a catastrophic scenario. In 10,000 years, the oceanic waters will cover the whole inhabitable parts of the Earth, whose surface will become like a uniform, liquid mirror, broken only by naked rocks emerging from the oceanic waters. This apocalyptic hypothesis was taken seriously and inspired by Manfredi (1732).

In 1731, Pope Clemens XII appointed Eustachio Manfredi from Bologna and Bernardino Zendrini* from Venice, two of the most leading scientists, to undertake a hydrological review concerning rivers, landscape and sewage in the coastal area of the Adriatic Sea in proximity of Ravenna (Fig. 1). At that time, Bologna and Ravenna belonged to the Papal State. Venice was an independent Republic facing the Adriatic Sea, at that time named the *Gulf of Venice*. The distance from Bologna to Venice is 130 km, from Bologna to Ravenna 68 km and from Venice to Ravenna 113 km.

Manfredi and Zendrini worked together and recommended that the rivers Ronco and Montone in Ravenna be diverted and sent the report (Zendrini and Manfredi 1731) to Cardinal Massei, the local public authority representing the Pope. They identified that the river discharge was directly related to sea level. As both Venice and Ravenna were maritime cities, facing the same Gulf, with the same challenges, Manfredi requested Zendrini to inform him about the situation in Venice, which was famous for coastal management and hydraulic works. The next year, Manfredi wrote a paper about SLR since Roman times (Manfredi 1732). This paper was internationally renowned because he reported three apparently coherent and independent issues, i.e. a case study in Venice, another in Ravenna and a theoretical explanation of the observed SLR, i.e. 15.1 cm century^{-1}.

Relying on Zendrini, Manfredi (1732) reported that, in 1500, on the side of the Ducal Palace, a stone walkway was built for the members of the Great Council who arrived in gondola for Council meetings. The walkway was originally built 1 Venice foot above the green algae belt. It must be noted that 1 ft is also the gunwale height of gondolas. Gunwale and

Fig. 1 The Venice Republic (green) and the Papal State (yellow). The location of sites cited in the paper is indicated. *Golfo di Venezia*: the Adriatic Sea. (Map of Italy by Homann Heirs, 1742)

walkway were at the same level to avoid council members stumbling upon the step when disembarking on the landing. However, in 1730, the walkway was reached by seawaters and covered in slippery algae, so that it was practically impassable. This detailed information is precious because it determines a definite rise of the algae belt (i.e. 1 Venice foot) and a definite time interval (i.e. from 1500 to 1730). Therefore, the related SLR rate (SLRR) was 34.76 cm/ 230 yr =1.5 mm yr^{-1}, or 15 cm century^{-1}. The uncertainty band was not defined. We know that the uncertainty in measuring CM is ±2 cm because we have measured it over different years, seasons, materials and exposures. Therefore, it is likely that the uncertainty was of the order of 2 in., while the signal was one order of magnitude greater, i.e. 1 ft. In conclusion, this is a reliable rate.

Manfredi (1732) reported another famous example, linking Venice to Ravenna (for the geographical, environmental and building similarities between Ravenna and Venice, see ESM). The Cathedral of Ravenna, built in AD 400, i.e. 1330 years before, had a second, older floor buried under the current one, 1 (Bologna) foot below "the average tides" (i.e. CM). Manfredi made a biassed calculation. He applied the SLR rate observed in Venice (in Venice foot) and found that over 1300 years, the level should rise by 5 ft and 9 oz. In 1730, the Cathedral was about 1 ft below the current sea level, and he argued that it was reasonable to suppose that it was originally built 4.5 feet above it. On this ground, he calculated the average rate obtaining 0.433 ft per century = 15 cm century^{-1}. At that time, this matching was considered highly relevant and an authoritative demonstration. Today we know that any comparison between Venice and Ravenna is merely speculative because the two intervals of time and the two LLS rates are different.

Finally, following Hartsoecker (1706), Manfredi provided a theoretical explanation for SLR. To evaluate the amount of mud transported by rivers, he sampled the water of rivers near Bologna in February, when the water was most turbid, and found that the fraction of mud suspended in water was in the ratio 1:174. Then he calculated the total amount of water that rivers deliver in 1 year into the sea and estimated the transport of solid materials that will deposit on the sea floor. He concluded that in 348 years, the sea will rise by 5 oz (i.e. 15.8 cm). Adding to this calculation the amount of sand and gravels transported with the mud, he found that in 230 years, the sea level will rise by 12 oz, i.e.16.5 cm century^{-1} that was very close to the value that he deduced from the Cathedral of Ravenna, i.e. 16.4 cm century^{-1}, and the value communicated by Bernardino Zendrini for Venice, i.e. 15.1 cm century^{-1}. Unfortunately, this was a too crude evaluation.

Giovanni Bianchi (pseudonym Planci 1739), physician and zoologist, was impressed by Manfredi and continued the discussion on the role that sedimentation had in rising the seabed and, consequently, the sea level, flooding the coastal areas.

Bernardino Zendrini* (1741) published a remarkable treatise on waters, hydraulic problems and solutions, i.e. 540 pages, especially focused on rivers, including their turbidity and deposition of mud, sand and gravel. To this aim, he welcomed the theory and calculations by Manfredi (1732) that was the most appreciated contribution of the eighteenth century. A more extensive work on the same subject was published posthumous (Zendrini 1811).

The famous Swedish astronomer and physicist Anders Celsius (1743), and his colleague Carl von Linné, alias Linnaeus (1744), botanist, zoologist and taxonomist, made a revolutionary discovery: in the Baltic Sea, the sea level was lowering. This announcement was surprising because it contradicted the logical theory of Hartsoecker (1706) and Manfredi (1732). Someone thought the sea was lowering at the poles and rising at the equator. Others started to think that the land too could have vertical motions.

Tommaso Temanza* (1761), a leading Venetian architect and scientist, summarized the state-of-the-art. He wrote: “CM is constantly rising. This fact is denied by some people, but acknowledged by others. We are observing it for two centuries. I have so many observations to prove it, that denying it would be against any evidence”. For instance, during excavations in Lizzafusina, on the Lagoon coastline, he found 30 in. (i.e. 87 cm) underground a floor made of square bricks, possibly of the Roman age. This finding was consistent with Sabbadino. However, both of them knew the depth but missed a precise time interval.

Giovanni Poleni* (1767), a leading physicist, mathematician, hydrologist and engineer of the University of Padua and member of the Royal Society, London, was appointed to study the regulation of the Lagoon waters and wrote a treatise on the rivers and their discharges into the sea. He also suggested an innovative regulation system where rivers were connected through canals with mobile gates, to stop the turbid water, favour the sedimentation in still water and allow clear water to enter the Lagoon. This project was partially applied.

The historian Cristoforo Tentori* (1792) focused on the laws that regulated the Venice Lagoon, highlighting the contribution made by Sabbadino, including his ideas about the role of winds, sea surges and rivers in transporting sand and causing SLR.

The naturalist, mathematician, geologist and philosopher Ermenegildo Pini (1793) discussed two hypotheses: is it the land that sinks, or the sea that rises? He considered that the marble columns of the Temple of Jupiter Serapis, on the volcanic area of Pozzuoli near Naples, facing the Tyrrhenian Sea, were found with borings of bivalve molluscs. This suggested that the columns sank below sea level and then re-emerged, showing a surprising land dynamism and change of trend.

The historian Giambattista Gallicciolli* (1795) reported and commented on a list of several examples of SLR in Venice, adding how they were interpreted, but this list was without the necessary details to calculate quantitative rates of SLR.

The historian, scientist and physicist Jacopo Filiasi* (1797) published the first edition of a monumental work, about the origins of Venice, its history and development, the Lagoon, hinterland and rivers. He accurately described the hydraulic regime of the Lagoon waters and the erosion of the small islands that need continuous protection and maintenance. Filiasi wrote that the SLR was deleterious for the coastal erosion and was responsible of the submersion of the most ancient areas in Venice (Book VI, Chapter XXV). Unfortunately, no quantitative values were reported. He mentioned that some early areas of the City were submerged over time and that somebody was concerned about SLR and the sedimentation inside the Lagoon (Book III, Chapter XXIX). However, he attributed the sinking to bad consolidation works (e.g. implanting poles) made to transform marshes into solid ground.

2.2.4 Nineteenth century

The German philosopher Immanuel Kant (1802, 1808) returned to discuss SLR, quoting Manfredi (1732) and Bianchi (Planci 1739), but was keen to exclude the idea that sea level was changed by sedimentation and sought a better explanation, without giving it.

Angelo Zendrini*, professor of mathematics and hydrology at the University of Padua and grandnephew of Bernardino Zendrini, published a series of papers. In the first paper (Zendrini 1802), he announced that the best strategy was to mark the sea level (i.e. CM) at a certain date and observe how it will change over time. Unfortunately, the oldest CM benchmark that has survived is dated 1841. He derived the idea from the example in the Baltic Sea after the discovery made by Celsius and Linnaeus. To start, he thought to take advantage of the famous stone walkway of the Ducal

Palace considered 64 years before by Bernardino Zendrini and published by Manfredi (1732). He wrote that in 1796, he returned to the same walkway, repeated the measurements made by Bernardino Zendrini and found that CM was 2 in. (i.e. 5.79 cm) higher.

Zendrini (1802) calculated that the rising rate was 3.5 to 4 ft per century, i.e. 10.1 to 11.6 cm century^{-1}, formally in agreement with the second evaluation by Sabbadino. However, following the style of that period, he avoided any discussion about the measurement uncertainties, but if we consider that it is ±2 cm for the lower and the upper level, the total uncertainty is half the signal.

In 1810, Angelo Zendrini returned Ducal Palace to update the CM level after 14 yr, but this time, he published a precise record of his results (Zendrini 1821). He measured the new CM level in seven different points, then he calculated the average (i.e. 8.36 in. = 24.2 cm) and found that the difference from the previous observations was 0.36 in. (i.e. 1.04 cm). He concluded that the rate was 3.12 in. per century, i.e. 9.4 cm century^{-1}. He commented that this result was in agreement with Sabbadino, while Manfredi (1732) was in excess of 30% and Cornaro of 300%.

However, it is not clear how the value 9.4 cm century^{-1} was calculated. If Zendrini extrapolated to 1 century the value found for 14 years, the rate would be 7.44 cm century^{-1}; if he calculated the mean between the rate found by Bernardino Zendrini and his rate, the result would be (15.1 + 7.44)/2 = 11.27 cm century^{-1}, in line with Sabbadino. Probably, he considered this average but miscalculated it.

The main weakness concerns the analysis of errors. In the Zendrini (1821) dataset, the span between the maximum and the minimum readings is 3.6 cm (i.e. 43% of the signal) and the standard deviation SD = 1.38 cm. If the measurement of the upper level in 1810 was affected by an error bar of ±1SD, and if one assumes the same for the lower level measured 14 years before, the total error bar is ±2SD. Applying this result to his secular rate, one obtains 9.4 ± 20 cm century^{-1}, where the uncertainty exceeds the signal by three times. Unfortunately, uncertainties were not yet considered, and measurements were repeated after too short time intervals. These obscure results increased the confusion and fed the public debate.

However, Zendrini (1821) indirectly gave a precious reference to relate a precise date, i.e. 1810, the floor of the Ducal Palace, and the height above CM. Describing the works made at the Ducal Palace in 1810, Zendrini indicated that the difference in level between CM and the floor was 24 cm. This observation led us to calculate that the sea level in 1810 was 59 cm lower than in 2020.

Jacopo Filiasi* (1811–14) published the second enlarged edition of his monumental book published in 1797. In both editions, Filiasi appears to be proud of the works made to preserve the Lagoon and its environment. However, a few years later, Filiasi (1817) criticized all hydraulic works, with a violence that Zendrini (1818) had to defend himself from this attack. Filiasi believed that every change brings new risks and that Venice became powerful for its favourable situation with a deep Lagoon, with fresh and salt waters, where ships could reach any inland site sailing on rivers or any other continent sailing on seas. He considered that having diverted rivers out of the Lagoon was detrimental to trades and to the Lagoon itself that remained unprotected against the sand transported by sea surges. Sabbadino and Filiasi were concerned about the siltation caused by the sea, Bernardino and Angelo Zendrini by rivers.

The geologist and naturalist Domenico Paoli (1838) presented some geological evidence that land had vertical movements and that Venice was affected by land subsidence. He reviewed Sabbadino under this new light, e.g. the S Marco Basilica that was sinking and the well dug in S Agnese by Mr. Eremitano. Angelo Zendrini (1845) contested land subsidence and returned to the old challenge of turbid rivers and highlighted his findings published in 1802 and 1821.

The scientist, politician and engineer Pietro Paleocapa* (1844) wrote a treatise on underground waters and artesian wells, making special reference to Venice and its Lagoon. He returned to Sabbadino (1543ca) and his interpretation of the well dug in S Agnese that originated the rate 1 ft per century. Paleocapa explained that the famous underground floor did not belong to an ancient building but was the bottom of an old, abandoned cistern. He contested the wrong dating as well as the rate of 35 cm century^{-1} advanced by Sabbadino and strongly supported by Cornaro.

The architect Emilio Campilanzi* (1840) returned to the Temple of Jupiter Serapis, Naples, and the vertical motions of the land, that could be the key to interpret Venice. However, he concluded relying on Sabbadino (1543ca) and Angelo Zendrini (1821). He agreed that the most probable value was 3.5 to 4 in. per century (i.e. 10.14 to 11.59 cm century^{-1}) and suggested to stay on the average, i.e. 10.90 cm century^{-1}. However, the cited values do not correspond exactly to the source for a misunderstanding. Zendrini (1821) wrote "3.12 in." (i.e. 3.12 in.), applying the decimal system that Napoleon imposed at the fall of the Venice Republic, in 1797. Campilanzi thought that Zendrini followed the traditional Venice style, where 3.12 in. separated by comma should be read 3 in. and 12 lines. Campilanzi considered that 12 lines were meaningless because 12 lines make 1 in., i.e. 3 in. and 12 lines = 4 in. He interpreted 12 a misprint for ½ and interpreted 3.5 inches = 10.14 cm. Again, the rate 4 in. per century was not derived from Zendrini but was introduced for a wider band, relying on Sabbadino.

Giovanni Ponti* (1888), Chief Engineer of the "*Genio Civile*" (public works), considered only Sabbadino (1543ca), i.e. 3–4 ft per century (11 ± 1.6 cm century^{-1}), and disregarded any other contribution.

3 Discussion

The archive and printed documents show that the road to reaching awareness and understanding SLR required centuries. A quantitative evaluation was even more difficult because an abundant documentation exists but misses precise metadata to interpret it and verify associated uncertainties. It is impressive to find that most of the literature was based on academic discussions without innovative content, and only a few scientists gave a real contribution. The most popular secular rates were not homogeneous, with different numerical values.

The first rate given by Sabbadino and supported by Cornaro, i.e. 1 ft per century, was dismantled by Paleocopa.

The second rate, i.e. 3–4 in. per century given by Sabbadino, was considered very authoritative but was grounded on uncertain metadata.

Manfredi was appreciated for the consistency of three independent evaluations, of which two should be rejected. The secular rate that Bernardino Zendrini communicated to Manfredi was the most reliable value, based on a sufficiently long time interval (i.e. 230 years) to reach a measurable rise (i.e. 1 ft), with signal larger than uncertainties.

Angelo Zendrini observed at too short time intervals, when the signal was lower than the uncertainties. His contribution was irrelevant or even increased confusion. However, Zendrini (1821) provided a useful information including a date, i.e. 1810, a precise reference, i.e. floor of the Ducal Palace, and the height above CM, that

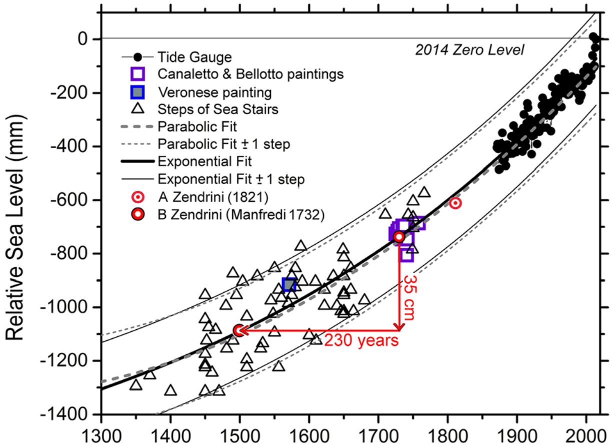

Fig. 2 The multiproxy series with highlighted the contribution of the written sources. (i) The two levels indicated by B. Zendrini (Manfredi 1732). The level in 1730 is the starting point; in 1500 (i.e. 230 years before), RSL was 35 cm lower. (ii) Level by A. Zendrini (1821). (Updated from Camuffo et al. (2017), by courtesy of Springer Nature)

allowed to know the level in 1810. This result was already known and used to build the multiproxy series.

The written documentary sources provide a new useful value: the rate 15.1 cm century^{-1}**,** representative of the 1500–1730 period (Manfredi 1732). This result may be compared with the multiproxy series (Camuffo et al. 2017) to test whether it matches with the other independent proxies (Fig. 2). The Manfredi rate is highlighted by overlapping the current level in 1730 and testing the position of the previous one in 1500. Manfredi reported that the level was 34.76 cm lower. A calculation with the multiproxy series gives 35.53 cm. The difference is 8 mm, that is smaller than the total uncertainty, i.e. ±4 cm deriving half from Manfredi (i.e. relying on the estimation made by Zendrini 1802) and half from the multiproxy series (12% uncertainty). Finally, the Manfredi rate is given by the ratio between 35.53 ± 2 cm and 230 years, i.e. 15.4 ± 1 cm century^{-1}**.** The multiproxy rate, calculated for the same years, gives 15.1 ± 1.8 cm century^{-1}, in strict agreement.

4 Conclusions

The analysis of four centuries of written documentary sources has provided new insight in the historical knowledge of the Venice Lagoon, the awareness of the challenges and the scientific approach. The data rescue found several case studies that have been carefully controlled, highlighting and explaining several misinterpretations. Only two sources had reliable data complete of metadata to interpret them, i.e. the walkway communicated by Bernardino Zendrini to Manfredi (1732) and another information by Angelo Zendrini (1821).

Manfredi (1732) reported that from 1500 to 1730, the sea level rose by 1.5 mm yr^{-1}. This value has been useful to verify the multiproxy series by Camuffo et al. (2017) and confirms the trend established with different proxies.

The evidence of the observed data in Venice does not confirm the reconstruction of the past sea level by Grinsted et al. (2010) who suggested a minimum level around 1730, preceded by a maximum culminated in the Medieval Warm Period around 1100–1200, similar for the reconstruction by Vermeer and Rahmstorf (2009), who also suggested a minimum level around 1700 and a maximum around 1400. If such a minimum level existed, it should be occurred in an unknown, earlier date.

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