“Acqua Alta” and the need for the Mo.S.E. project

Managing the coastal flood in Venice

May 14, 2020

"Acqua Alta" and the need for the Mo.S.E. project

Managing the coastal flood in Venice

University:
TU Delft

Course code:
CIE4061-09

Date of submission:
May 14, 2020

Supervisors:
Prof. Dr. Ir. S.N. Jonkman
Dr. Ir. A. Antonini
Dr. Ir. M.A. Diaz Loaiza
Dr. E.J. Houwing

Author names and student numbers:

G. Godlewski	5009839
L. Caporalini	5157765
B. Deuss	4480902

TU Delft

NWO Netherlands Organisation for Scientific Research

Preface

The SAFElevee project at Delft University of Technology focuses on levee performance and failure, and analyses the interrelated processes of (initial) failure of a levee and breach development, both at a system-macro scale as well as for individual failures. To support the different work packages of this project an international levee performance database has been developed. A second section provides more details on the database and the type of information provided by the database.

This report is the product of a multidisciplinary project we conducted as part of our M.Sc. program at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. The multidisciplinary project is performed on behalf of Prof. Dr. Ir. Bas Jonkman. It is part of a fact-finding research for the flooding of Venice in November 2019, conducted by the Delft University of Technology. The report focuses on the meteorological and physical description of the flood event, the protection of the lagoon surrounding Venice and the impact the flood event had on the area.

We hope that this report will contribute to the fact-finding research of the Venice flooding in 2019 and to water safety of Venice in general. We also want to address a special word of thanks to our supervisors Dr. Ir. Manuel Diaz Loaiza, Dr. Ir. Alessandro Antonini, Dr. Erik-Jan Houwing and Prof. Dr. Ir. Bas Jonkman, who have supported us during the process and were always happy to help.

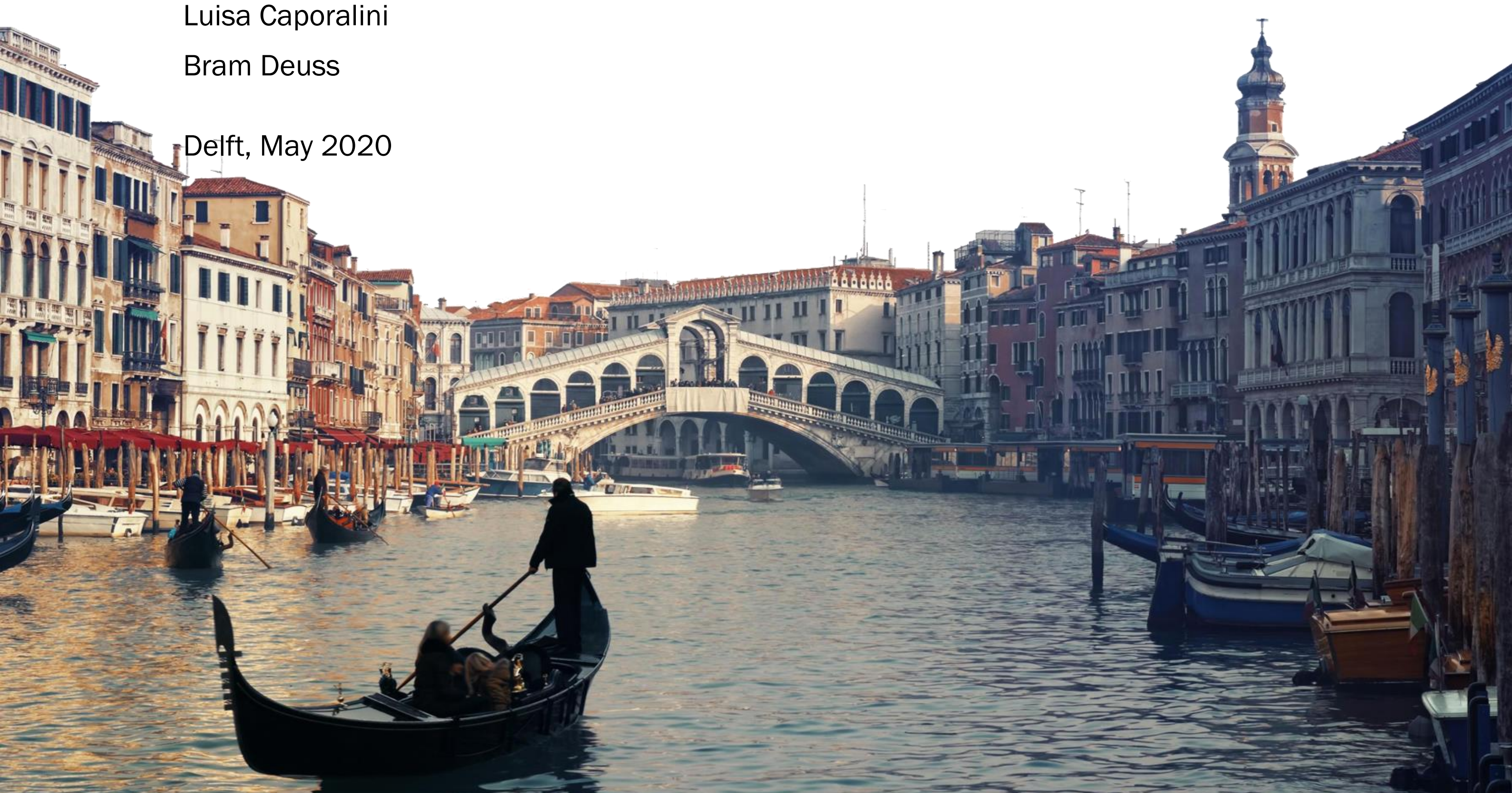
The report was developed in collaboration with Dr. Ir. Giovanni Cecconi, director of the Venice Resilience Lab and former director of the Control Room, who granted us with an interview, providing precious information, vital to write the report. Also Dr. Ir. Peter van Westendorp, civil engineer professional at Strukton Civiel Projecten B.V., collaborated proving information about Strukton's experience within the Mo.S.E. project and CNR-ISMAR Venice helped providing precious data and information about the lagoon hydrodynamics.

Gabriela Godlewski

Luisa Caporalini

Bram Deuss

Delft, May 2020



Acknowledgments:

This research was supported by the NWO project SAFElevee No. 13861. Special thanks and mention to Dr. Sandra Fatorić for her help with the cultural heritage assessment and guidance, to Ir. Giovanni Cecconi for sharing literature, organizing the failed field trip (not executed due to coronavirus crisis) and the interview performed. Many thanks also to CNR-ISMAR, particularly to Dr. Christian Ferrarin and Dr. Alvise Benetazzo for the provided data and detailed information on the lagoon hydrodynamics. Finally, to Dr. Sebastiano Carrer (Thetis S.p.A.), Ir. A. Scotti, Dr. Alessandra Crossato (IHE), Ir. Peter van Westendorp (Strukton) for their priceless comments and experience with the MoSE project, to Prof. G. Seminara (University of Genoa) for his detailed reconstruction on the development of the studies that interested the Venice lagoon and to the Comune di Venezia - Centro Maree for making the sea level data available.

Index

List of abbreviations used

ANAC Autorità Nazionale Anticorruzione (*Lit. National Anti-Corruption Authority*)

CDF Cumulative Distribution Function

CNR Consiglio Nazionale delle Ricerche (*National Research Council*)

CTR Click-Through Rate Control Scenario

CVN Consorzio Venezia Nuova (*Lit. New Venice Consortium*)

DTM Digital Terrain Model

EC European Commission

EIA Environmental Impact Assessment

GEV Generalized Extreme Value

GPI General Plan of Interventions

ISPRA Istituto Superiore Protezione e Ricerca Ambiente (*Lit. Italian Institute for Environmental Protection and Research*)

JSC Juridical State Council

MC Municipality of Chioggia

MCH Ministry of Cultural Heritage

ME Ministry of Environment

MIT Ministry of Infrastructure and Transport

Mo.S.E. Modulo Speriementale Elettromeccanico (*Lit. Experimental Electro-mechanic Module*)

MoW Magistrate of Waters

MPW Ministry of Public Works

MSL Mean Sea Level

MV Municipality of Venice

OSM Open Street Map

PDF Probability Distribution Function

PIOPTV Provveditorato Interregionale per le Opere Pubbliche per il Veneto, Trentino Alto Adige e Friuli-Venezia Giulia (*Lit. Inter-regional Superintendence for the Public Works of the Trentino Alto-Adige, Friuli-Venezia Giulia and Veneto regions*)

(Q)GIS Geographical Information System

REA Riequilibrio e Ambiente mega-project (*Lit. Rebalance and Environment*)

SIO Script Institution of Oceanography

TAR Administrative Regional Court

TOE Technological, Organizational and External (framework)

UNESCO United Nation Educational, Scientific and Cultural Organization

WWF World Wide Fund for Nature

Summary

The city of Venice has been prone to flooding throughout its history. However, flooding has recently been occurring more often than before. As a result, engineers have collaborated to come up with a potential solution to the flooding. This solution, a mobile barrier known as the Experimental Electromechanical Module (Modulo Sperimentale Elettromeccanico, or Mo.S.E.) has been in progress for quite some time now and is therefore still not functional. On 12 November 2019, an extreme high water level event occurred with the second highest recorded water level in history. The flooding event should have been prevented by the construction by a flap gate storm surge barrier, a project started after the 1966 historical high water event, which takes the name of Mo.S.E. project. In this paper, the 2019 event is analyzed, investigating the causes of the event and the design criteria of the Mo.S.E. barrier project in terms of its structure, construction process and completion state at the time of the event.

The meteorological and hydrological causes of the 12 November 2019 is studied to better understand what caused the event. If the causes of an event are understood, a solution to similar future events can be more easily determined. Historic water level data is used to better understand the hydraulic conditions within the Venice Lagoon. Existing research projects that utilized similar data are studied to estimate the return periods considered in the design of the Mo.S.E. barrier. The return period for the 12 November event (187 cm) was found to be about 130 – 140 years. The return period for the water level at which the Mo.S.E. barrier is designed to be fully closed (110 cm) is 5 – 7 years. The effects of climate change and subsequent eustacy are also analyzed to determine how this would affect the return periods of both the 12 November 2019 event and the barrier closure level. Analysis of estimated future return period data predicted that the return period range for the 12 November event would become more frequent decreasing from 130 – 140 years to 50 – 100 years while the return period for the Mo.S.E. barrier closure would decrease from 5 – 7 years to 2 – 5 years.

An estimation of the flooded buildings and roads is made. Surface elevation data is compared with the water level of the November 2019 flood event. In this way information is gained about what areas were flooded, by using downloaded from Open Street Maps, information about all buildings and roads, including their location, are obtained. Analyzing this data, results in information about what buildings and roads are flooded. These results, together with numbers of damage per flooded object, are used to make an estimation of the total direct damage due to the flood event. The estimated total direct damage amounts to €870 million. The estimated damage to cultural heritage amounts to €244 million. Also, the case in which the Mo.S.E. barrier would have been operational during the November 2019 flood event was investigated. If the barrier had closed, the total direct damage would have been €257 million.

Conclusively, an analysis of the management system of the Riequilibrio E Ambiente (REA, Lit. Rebalance and Environment) mega-project and the Mo.S.E. project is conducted to visualize the main failures and delay causes which lead to the circumstances of incompletion of the barrier at the time of the 2019 flood event. Through a careful analysis of the main events and technical problems encountered throughout the planning and construction of the barrier, the leading causes of this delay are found to be uncertant althought many sources cite the political circumstances, the uncareful definition of project objectives and extreme levels of project complexity. Currently, the completion of the storm

surge barrier is scheduled to be at the end of 2021. In 2019, the construction of the barrier was found to be completed at its 94%, signifying an 8-year delay past the original completion date of 2012, which was determined at the begging of the construction works in 2005. The Mo.S.E. barrier project is merely one part of a much larger mega-project designed for the safeguard of Venice which was meant to be completed in 1985. While the Mo.S.E. barrier is delayed almost 8 years, the entire project is delayed by a total of 26 years.

It is recommended to direct further researches to future impact, considering climate change, and the amount of damage for certain return periods and the impact of the Mo.S.E. barrier on this last.

Chapter 1: Introduction

Luisa Caporalini, Bram Deuss, Gabriela Godlewsi

1.1 About the report

Students at the Delft University of Technology present this fact-finding study as a multidisciplinary project converging hydraulic engineering and project management perspectives. The goal of this study is to produce a clear response to the developed researched question, stated in the following paragraph.

The Maritime Republic of Venice and its surrounding lagoon create a distinctive environment in which construction techniques and artifacts give a unique quality to the city's charm (Lane, 1973). Similar to many other coastal regions, sea level rise resulting from climate changes in Venice lagoon is expected to increase erosion along with frequency, intensity and height of tidal floods (locally called Acqua Alta, *Lit. High Water*); and loss of habitat and biodiversity (S. Munaretto, 2012). In 2019, Venice lagoon was subjected to an exceptionally high tide that caused significant damages to Venice's historic city center and resulted in the death of two people. This flooding event was recorded to be the highest tide since 1966, when another exceptionally high water level occurred and also resulted in extreme flooding. Following 1966, measures were taken by the Italian government to protect the city of Venice and its lagoon. Among the planned interventions we can find the construction of the Mo.S.E. storm surge barrier, planned to be completed in 2012, but found to be still under construction in 2019.

The objectives and structure of this report are defined in the following paragraphs, while the next chapter outlines a system overview of Venice lagoon and contextualizes the object of our team's research.

1.2 Objective

The objective of this report is to study facts surrounding the November 2019 flooding event that occurred in Venice as well as the design and operation of the Mo.S.E. barrier. To do so, this report attempts to answer to the following research question:

- What are the causes, circumstances and impacts of the 2019 Venice flood event and the performance and status of the Mo.S.E. barrier?

This one question concerns a complicated matter and it is therefore difficult to answer succinctly. Thus, the report consists of three different research projects which each cover a distinct part of the main research question and have their own research questions. This paper does not intend to test hypothesis nor sustain theories, it rather analyses verified facts and circumstances around the 2019 Venice flooding event.

The first part considers the hydraulic conditions of the lagoon and the November 2019 storm surge. This part of the project considers the following research questions:

- What were the hydrometeorological conditions that lead to the 12 November 2019 event?

- What was the return period for the 12 November 2019 event?
- What is the return period for the sea level of +110 cm at which the Mo.S.E. is designed to close?
- What are the return periods of the climate change scenarios?

The second part of the research project has to do with the impact and damages which result from the November 2019 flood event. This part considers the following research questions:

- What were the flooded areas during the 2019 flood event and what were the water depths?
- What were the priced and unpriced damages as a result of the 2019 flood event?
- What have been flood prone areas in the past?
- If the barrier would have worked, how would it have affected the water levels and the damage?

The third part covers the Mo.S.E. project itself and its completion delay. This final part of the project considers the following research questions:

- What is the Mo.S.E. project and in what context can be identified?
- Which typical Large Infrastructure Project aspect most affected the Mo.S.E. project process?
- Should the barrier have been operated during the emergency flooding event of 2019?

Prior to these three main parts, introductory research is carried out to get a system overview. This introduction considers the following questions:

- What is the Venice lagoon layout and what is its history?
- What was the lagoon status in 2019?

1.3 Structure of the report

The structure of this report is as follows:

First, a system overview of the Venice lagoon is given to provide more insight in the concerning research area in chapter 2.

Chapter 3 covers the research of the hydraulic conditions and the November 2019 storm surge.

Chapter 4 covers research of the impact and damages due to the November 2019 flood event.

Chapter 5 covers the research of the Mo.S.E. project and its delay.

Lastly, in chapter 6, the conclusions of the main research projects are compiled, and further recommendations for future research projects are included.

Chapter 2: System overview

Luisa Caporalini, Bram Deuss, Gabriela Godlewski

Venice and the Mo.S.E. barrier are located in Northern Italy, in the Venice Lagoon. The subject of our investigation is the Venice Lagoon, which holds the sub-subjects specifically investigated which are the City of Venice, the hydraulic characteristics of the area, and the Mo.S.E. project itself. The research questions that this introductive chapter aims to answers are the following:

- What is the Venice Lagoon layout and what is its history?
- What was the Lagoon status in 2019?

2.1 Venice Lagoon

The Venice lagoon has an area of about 550 km², of which only 8% of this area consists of emerged land: the city of Venice, about fifty smaller islands, the coasts, the embanked fishing valleys and the artificial filler boxes. Since this area is located in the transition from the land to the sea, the tide is very influential in the area, especially in the canals. The canals cover 11% of the Venice Lagoon. The remaining 80% consists of tidal flats, non-vegetated muddy plains that emerge only during exceptional low tides, and vegetated sandbanks areas occasionally submerged by high tide (Dabala & Campostrini, 2017).

2.1.1 Configuration

The lagoon is separated from the Adriatic Sea by a series of shores called (from north to south) Sottomarina, Pellestrina, Lido and Cavallino. The sequence of shores is separated by three lagoon mouths: Lido, Malamocco and Chioggia (see Figure 1).

The Port of Lido, also known as the Port of San Nicolò, is the northern access to the Venice Lagoon. It separates the Cavallino and Lido shores. The Malamocco Inlet is the central access to the Venice lagoon, and it divides the Lido and Pellestrina shores. Chioggia, the southern-most inlet, is located between the Pellestrina and Sottomarina shores.

The watershed has a surface area of roughly 1,850 km² (Regione del Veneto, 2000). On average, the water exchanged between the lagoon and the sea is 400 million m³. The average variation of the tide in the lagoon is about 1 m, as it is subjected to variations caused by astronomical and meteorological factors (CVN, Non solo il MOSE, 2014).

At the three lagoon inlets, to protect the city of Venice and all the other lagoon inhabited parts from the risk of flooding, the Italian government planned the construction of a mobile barrier system, the Mo.S.E. project. The project will be referred to throughout the entire research and will be analyzed in further detail in chapter 5.

2.1.2 Ecology

In the Mediterranean area, the Venice Lagoon represents an exceptional example of semi-lake habitats, made vulnerable by irreversible natural and climatic changes. In this interconnected ecosystem where the salt marshes (muddy soils that are submerged or emerged depending on the tidal level) are of equal importance to the islands, it is just as necessary to protect the elevated house, fishing villages and rice fields as it is to protect the historic palaces and churches (CVN, 2019). Venice symbolizes the historic struggle between humanity and the elements. The whole area is defined by UNESCO[1] as a World Heritage Site.

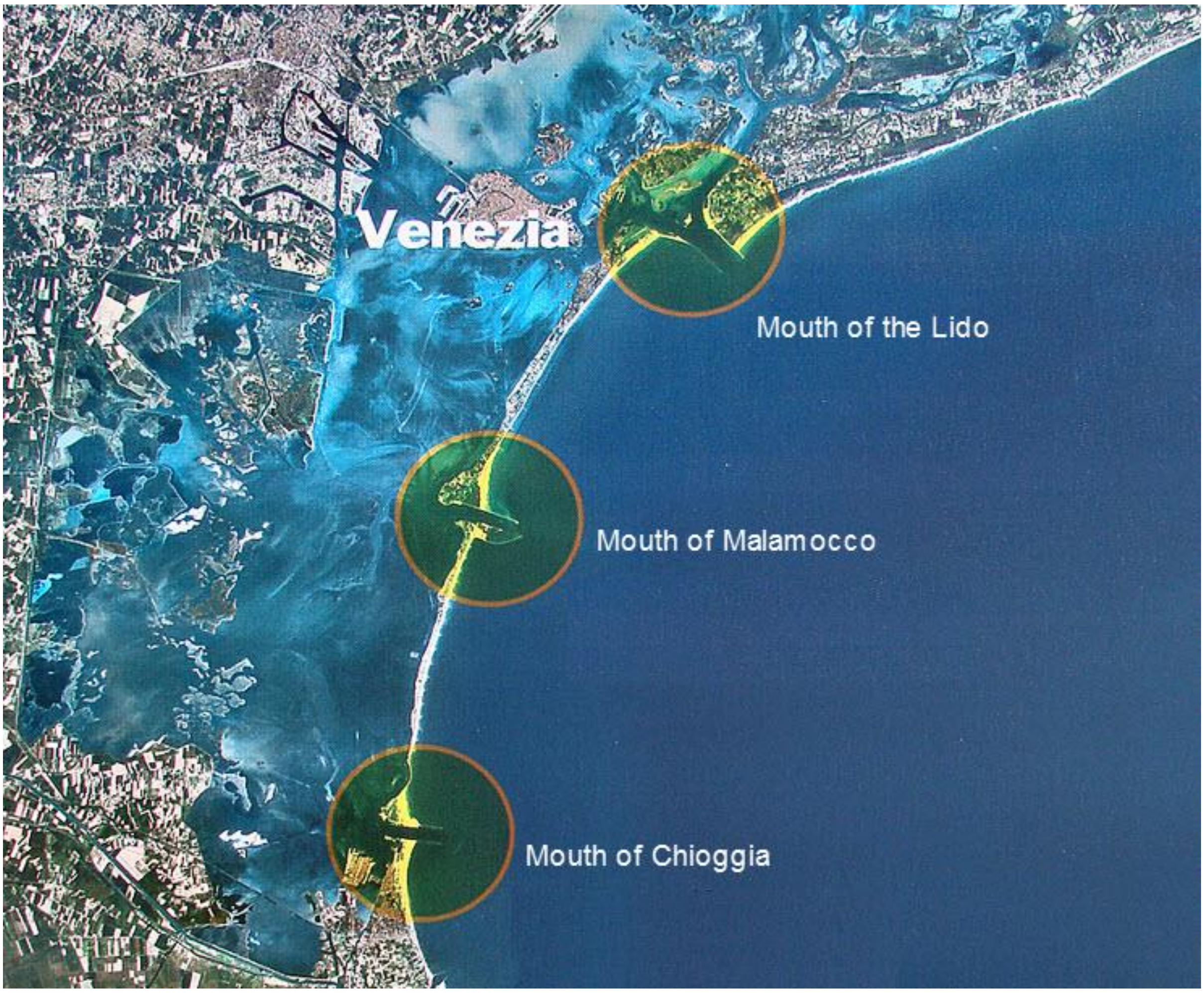


Figure 1 - Overview of Venice Lagoon (Keane, 2013)

2.1.3 Morphologic History

The formations of the City of Venice and its aquatic landscape are the result of a dynamic process which illustrates the interaction between humanity and the natural ecosystem of their environment over time.

The primeval lagoon reached its present size approximately 6,000 years ago, though it was smaller for a while before then. At this time, the flow of water in the area was made possible through eight sea openings as opposed to only three that exist today (L. Carbognin, 1984). The lagoon morphology, consisting of shallows, mud flats, salt marshes, islands and a wide network of channels, was subjected to the great mutability of these factors which had generated and developed the morphology throughout the ages. Among these, the activity of the main lagoon tributaries (Adige, Bacchiglione, Brenta, Sile and

[1] United Nations Educational, Scientific and Cultural Organization

Piave) was determinant and almost made the area a marshland rather than a lagoon. Together with the increase in the depth of the lagoon due to subsidence and eustatic rise, human activities have now inverted the lagoon's natural tendency to silt up and instead triggered the opposite process, slowly transforming it into a sea environment (D'Alpaos, L'evoluzione morfologica della Laguna di Venezia attraverso la lettura di alcune mappe storiche e delle sue carte idrografiche, 2010).

Over the years, the lagoon has been subject to many flooding events due to its unique exposure to wind and sea forces. Although inhabitants of Venice and the surrounding areas are familiar with these events, some flooding events have reached such a water level that posed a legitimate threat to both the residents and the environment. The exceptionally high tides that had been recorded at Punta della Salute since 1930 are described in the timeline shown in Figure 2 (Comune di Venezia, 2016):

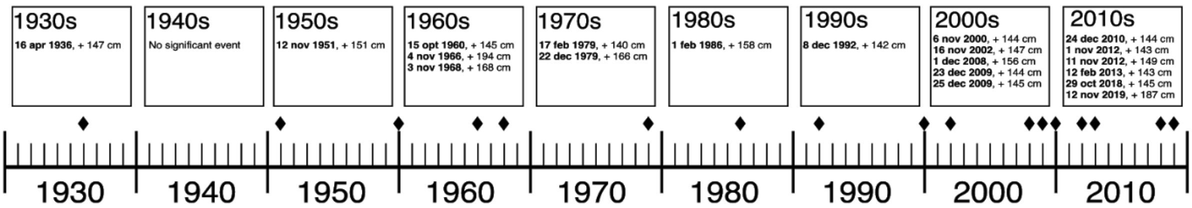


Figure 2 - Timeline of exceptionally high tides (Comune di Venezia, 2016)

Human activity has profoundly changed the appearance and morphological balance of the lagoon since the time of the first settlements. Over the centuries, the initially numerous port mouths have been reduced to the current three. The shores that separated the lagoon from the sea were reinforced and stabilized with the powerful works of the Murazzi, a very long eighteenth-century dam system built in 1782 from Istrian stone placed along the external lagoon perimeter for defence. These dams were damaged during the exceptionally high tide events on 1825 and in 1966 (Colognesi, 2017).

Four major rivers – Sile, Piave, Brenta, and Bacchiglione – once drained into the Venice Lagoon, transporting abundant supplies of fresh water, sediment and organic matter. Prior to the year 1500, the rivers entering the lagoon contributed approximately 700,000 m^3 of fine-grain material, most of which was deposited to form fringing salt marshes and mud flats. An additional 300,000 m^3 of sand entered the lagoon from the sea and formed flood-tidal deltas. By 1650, all major rivers had been diverted to bypass the lagoon and discharge directly into the sea to avoid lagoon siltation. This diversion, followed by the construction of breakwaters at the lagoon inlets and the increased dredging of lagoon channels for navigation purposes, had a significant impact on the lagoon morphology (Suman, Guerzoni, & Molinaroli, 2005).

These human interventions compromised the natural equilibrium of the area and lead to the decline of numerous inhabited centres, such as Torcello, Costanziaco and Ammiana.

2.2 The History and Heritage of Venice

The history of Venice started in the 5th century A.D. as people tried to find refuge from raiding Visigoths, Huns and Lombards on islands in the lagoon. They first settled on the island of Torcello and later the spread to surrounding islands (lonelyplanet.com, 2020). Eventually, these settlements grew out to become a powerful and prosperous city.

This prosperity resulted in thriving architecture and art. As touched upon earlier, the whole of the city of Venice and its lagoon are an UNESCO heritage site. Within the City of Venice, many buildings are individually protected as cultural heritage as well.

On the UNESCO website, the following is stated about the heritage of Venice: 'The UNESCO World Heritage property comprises the city of Venice and its lagoon situated in the Veneto Region of Northeast Italy. Founded in the 5th century AD and spread over 118 small islands, Venice became a major maritime power in the 10th century. The whole city is an extraordinary architectural masterpiece in which even the smallest building contains works by some of the world's greatest artists such as Giorgione, Titian, Tintoretto, Veronese and others.' (UNESCO, 2020)

Nowadays, the economy in Venice is mainly driven by the tourism industry. A minority of Venice's population, about 53,000 people, live in the historic center. Roughly four times as many live on the surrounding mainland and estuary of Venice (DW, 2019). Venice's city center has seen a slow trickle of people leaving the city, as the constant flood risk has made life and business operation for many people untenable (NBC News, 2019). Of about 53,000 residents in the city's center, Venice lost over 800 residents in 2018 alone (Jacobson, 2019).

The history of the population in the city of Venice is shown in Figure 3 (Venipedia, 2019). Note the declining trend in population since the mid-20th century

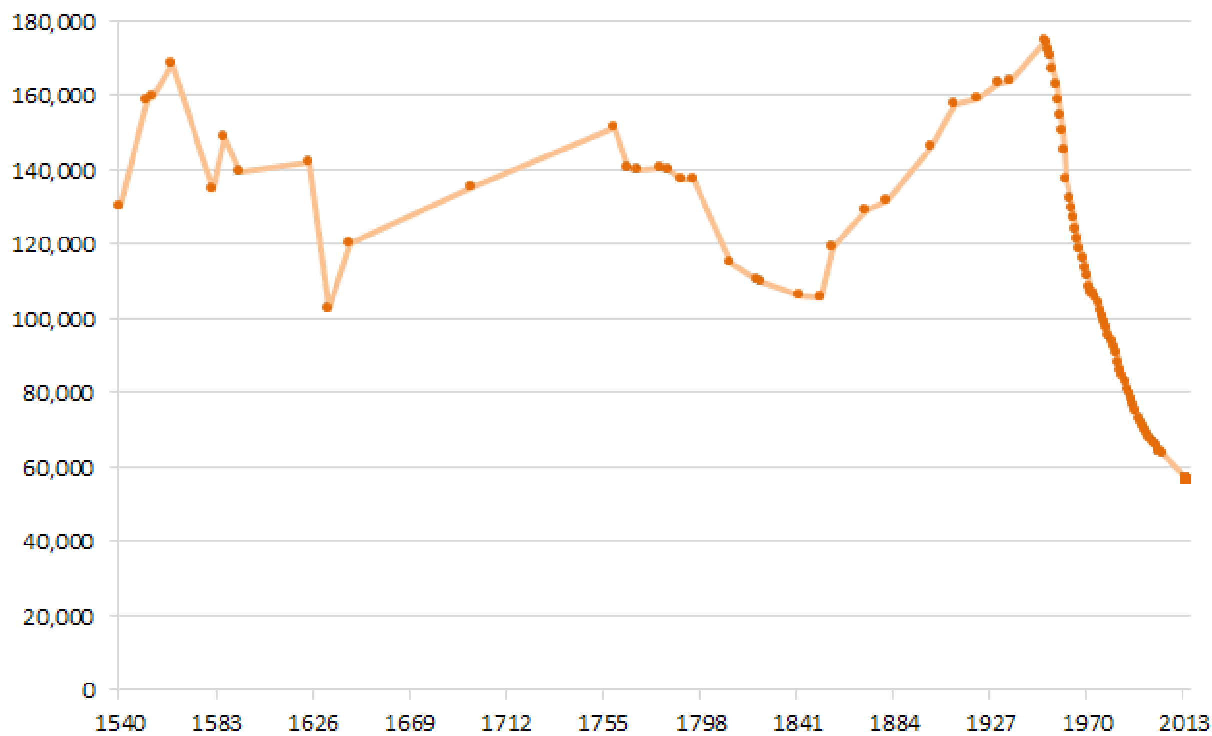


Figure 3 - Population of Venice from 1540 to 2015 (Venipedia, 2019)

Chapter 3:
Hydraulic Conditions of the Venice Lagoon and Analysis of the November 2019 Storm Surge

Gabriela Godlewski

The focus of this section is listed as follows: to provide the results of research into statistical analyses of high-water levels that occur in the Venice Lagoon; to explain the physics behind the 12 November 2019 event; and to understand how these factors are relevant to the design of the Mo.S.E. barrier. The frequency at which certain water levels occur, also known as the return period, was studied to gain a better understanding of the hydraulic conditions in Venice. Research into statistical analyses of the water levels in Venice was performed to find the frequency at which these events occur. From this analysis, the heights of the 10-year, 100-year, and 200-year events were found, and the corresponding return periods for the November 2019 storm surge event were preliminary estimated as well. Sea level data used in this chapter was taken from the early 20th century up to 2019, but the return period data was found using information available up to 2005. This was done to better understand the conditions for which the Mo.S.E. barrier was designed. The Mo.S.E. barrier is designed to close completely at a fix water level (110 cm) and the correlated return period of this water level was estimated as well. The results suggest that Mo.S.E. barrier was designed for a water level with a return period around 10 years while the 12 November 2019 event (187 cm) was estimated to be characterized by a return period of 135 years. The statistical analysis of the hydraulic conditions provides a well-rounded understanding not only of the conditions in the Venice Lagoon but also the criteria required to design an effective flood prevention mechanism.

3.1 Introduction

The location and configuration of Venice makes the city highly vulnerable to damage from severe storms and high-water level events. A layout of the city of Venice can be seen in Figure 1 in Chapter 2. Stations that collect water level data are also situated in the area. For this fact-finding research, the data used for the Venice Lagoon was collected at Punta della Salute and data for the Adriatic Sea outside the lagoon was collected at Diga Sud Lido. The location of these stations is shown in Figure 4. This map shows not only the orientation of the inlets but also the location of Punta della Salute where the data is recorded in Venice, and Diga Sud Lido, which recorded data for the Adriatic Sea.

Figure 4 – Venice Lagoon map extract showing Punta della Salute and Diga Sud Lido(Google Earth)

Historically, Venice was always threatened by a myriad of issues including subsidence, eustasy, and extreme flooding. With climate change further worsening certain threats such as sea level rise, increased frequency and duration of storms, and increased amount of rainfall, the vulnerability of Venice has increased significantly. Not only is Venice a city of great historic and cultural importance, but the city is also home to more than 260,000 residents, making protecting Venice from such natural extreme events a high priority. The methods to protect the Venice Lagoon and therefore the City of Venice were decided upon by also considering hydrological data. The data was used to answer the following research questions:

- What were the oceanographic and meteorological conditions that lead to the 12 November 2019 event
- What was the return period for the 12 November 2019 event?
- What is the return period for the sea level of +110 cm at which the Mo.S.E. is designed to close?
- What is the return period of the climate change scenarios?

These questions were answered by researching existing data related to the high water level events and the return periods of water levels in the Venice Lagoon. First, the meteorological and hydrodynamic conditions that preceded the 12 November 2019 event were researched to develop a better understanding of the high water level that occurred that day. Then, raw data, which provided the total water level at Punta della Salute, was gathered and filtered using the recursive Chebyshev Type II filter. This separated the data into the components corresponding to the meteorological and the astronomical tide, which provided a better understanding of the cause behind the 12 November 2019 event as well as another high water level event in October 2018. This method is further elaborated upon and the results of the method can both be found in section 3.2.2. The data acquired through research of various return period calculation methods was used to estimate the return periods of the 12 November 2019 event as well as the chosen closure level of the Mo.S.E. barrier. This data was then used to estimate the time at which the Mo.S.E. barrier would have closed, if it were functioning at the time of the November 2019 event, as well as how long the barrier would have been in the raised position. The effect of climate change on future sea levels as well as future return periods for extreme water levels was also explored by researching previous works.

To provide a better understanding of the content in this section, some key definitions were included

Astronomical tide: the tidal levels and character that come as a result of the gravitational pull from the earth, sun, and moon (Judith Bosboom, 2015).

Meteorological Storm surge: a rise in the water level that comes as a result of changes in wind and atmospheric pressure caused by storms.

3.2 Astronomical tides and Meteorological storm surge

Since the most extreme water level event hit Venice in 1966, the Municipality of Venice has been working with engineers from all around the world to produce a solution to protecting Venice. In order to come up with such a solution, data pertaining to historic water levels in the Venice Lagoon must be analyzed. Data used for this fact-finding project was provided by the Municipality of Venice and pertains to the water level height from 1983 – 2019. This data was collected at Punta della Salute, a station located in Venice (see map above, Figure 4).

Over the past decade, Venice has on average experienced daily high water levels ranging from +65 to +75 cm above datum and daily low water levels ranging from -20 cm to -30 cm below datum, therefore fluctuating about 85 to 105 cm daily. The mean sea level in Venice is +34 cm above datum. Figure 5 illustrates the water levels over time. There is an observable steady increase in the sea level as time goes on. The moving averages confirm an increase in the average sea level during this time period. This is not only caused by global eustasy but also in part due to subsidence that occurs locally in Venice. Subsidence refers to the sinking of the city itself, and this phenomenon is caused by ground compaction from the weight of the buildings and groundwater pumping from beneath the city (Live Science Staff, 2012). Over the 20th century, it is estimated that Venice was sinking at a rate of 0.5 mm/yr and has lost a total of 12 cm of elevation (Brambati, Carbognin, & Quaia, 2003). From the data at the Punta de la Salute we find a similar trend: sea leve rise of 16.76 cm in 33 year ~ 0.5 mm/yr (see figure 8)

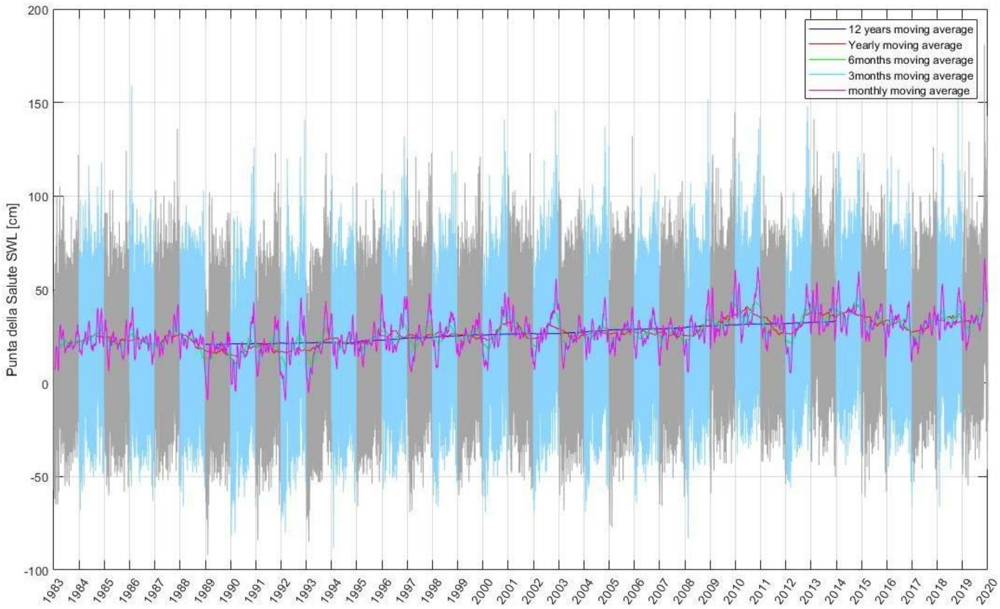


Figure 5 - Sea level rise data from 1983 – 2019 is compiled.

Further analysis was conducted to separate the data caused by meteorological forcing and the data caused by astronomical data. The meteorological storm surge are caused by variations in recurring weather conditions that are not periodic and happen more randomly, such as changes in atmospheric pressure, wind patterns and precipitation. Astronomical tides, on the other hand, are controlled by the periodic gravitational pull of the Earth, Sun and Moon with some influence from the Earth's atmosphere (Judith Bosboom, 2015).

3.2.1 Tidal Components of the Venice Lagoon

The astronomic tides experienced in Venice are the summation of different harmonic components. The tidal components are named for the astronomical influence. Below is a chart of the tidal components and their respective amplitudes and phases that comprise the Venetian tide (Brambati, Carbognin, & Quaia, 2003). Each constituent (M2, S2, N2....) is characterized by the average amplitude and phase observed in the Adriatic Sea and in the Venice Lagoon. The tidal constituents indicate that the semi-diurnal tides (M2, S2, N2, K2) are larger in both the Adriatic Sea and the Venice Lagoon than the diurnal tides, though the overall tidal characterization can be categorized as mixed, predominantly semi-diurnal (Judith Bosboom, 2015).

Table 1 – Tidal Components of the Venice Lagoon (Tomas, 2008).

	M2		S2		N2		K2		K1		O1		P1	
	Amp (cm)	Phase (deg)	Amp (cm)	Phase (deg)	Amp (cm)	Phase (deg)	Amp (cm)	Phase (deg)	Amp (cm)	Phase (deg)	Amp (cm)	Phase (deg)	Amp (cm)	Phase (deg)
Adriatic Sea	11.5	171.5	7.3	166.8	2.1	175.2	2.3	160.6	10.2	65.1	4.1	54.4	2.8	56.2
Venice Lagoon	22.6	302.2	14.0	294.0	4.0	297.0	4.7	288.4	18.2	94.9	6.7	82.2	5.2	96.0

3.2.2 Analysis of Tidal Data

In order to separate the meteorological storm surge from the astronomical tide, a filter analysis was applied to the data provided by the Municipality of Venice, which was detrended to remove the effect of sea level rise and other long period phenomena, such as subsidence and eustasy. The tides were separated in order to understand which had the highest impact on the mean water level. To run the analysis, the recursive Chebyshev Type II filter was applied to the data. The filter, designated "lowChebyshev" in the data, has a stopband for up to a 26-hour period with a designated attenuation of 30 dB, and a passband for a minimum period of 30 hours and a ripple magnitude of 3 dB. Although higher frequency data is lost in this analysis, the resulting data is a reliable estimation of the tidal events in the Venice Lagoon (Jenny M Brown, 2012). The results of the filter analysis are shown in the figures below.

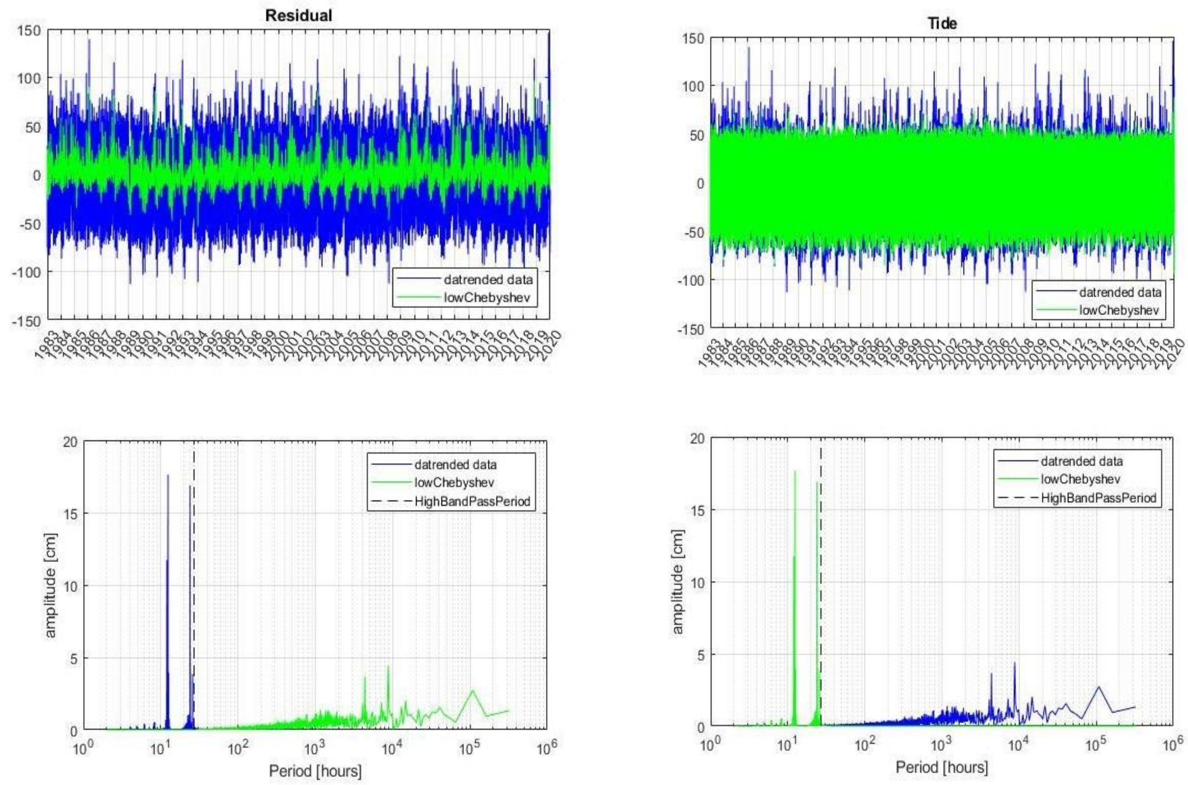


Figure 6 – Top left: The residuals from the Astronomical tide is superimposed in front of the detrended sea level data (blue). Top right: The astronomical tide is shown in green superimposed in front of the detrended sea level in blue. Bottom left: The periods related to the meteorological storm surge highlighted in green. Bottom right: The periods related to the astronomical tide are highlighted in green.

3.3 Meteorological Summary of 12 November 2019 Event

The November 2019 event in Venice was caused by several complicated meteorological phenomena in the atmosphere occurring at the same time as hydrologic abnormalities in the water below. The Venice Lagoon was experiencing an exceptionally high astronomical tide of 140 cm. Near the central-southern part of Italy over the Tyrrhenian Sea, a low-pressure phenomenon generated winds from the south-east, known as Scirocco. At the same time, a smaller cyclonic formation rotated in the atmosphere above the northern Adriatic Sea near the Venice Lagoon, which also generated winds from the northeast known as Bora. This wind combination often results in high water events. This vortex intensified the Scirocco and Bora winds to average speeds of 70 km/hr with gusts of 110 km/hr. A warm front also arrived above Venice, increasing the air temperature by up to 6°C while the barometric pressure continued to rapidly decrease by 3 mb in 30 minutes. The vortex caused the Bora winds to rotate and blow from the south west, while also intensifying the wind speed to 100 km/hr on average and 110 km/hr gusts. Once the atmospheric pressure minimum and southwestern rotation passed over Venice, the water level descended suddenly. This descent delayed the natural tide propagation, causing a critical sea level height, which coincided with the intense southwestern winds. This resulted in a rapid sea level rise, flooding and damaging a greater part of the city (Ferrarin, 2019).

The maximum sea level recorded during this event was 187 cm at 22:50 recorded at Punta della Salute. At the same time, the total water level at Misericordia Station was measured to be 173 cm and the tide at the North of Venice Station was measured at 160 cm. This indicates that the peak of the extreme water level event occurred near the center of the Venice Lagoon, closer to the coast of the city of Venice.

The maximum value of 187 cm recorded at Punta della Salute is the summation of the 127 cm astronomical tide, 26 cm from meteorological storm surge, and 34 cm mean sea level (Ferrarin, 2019).

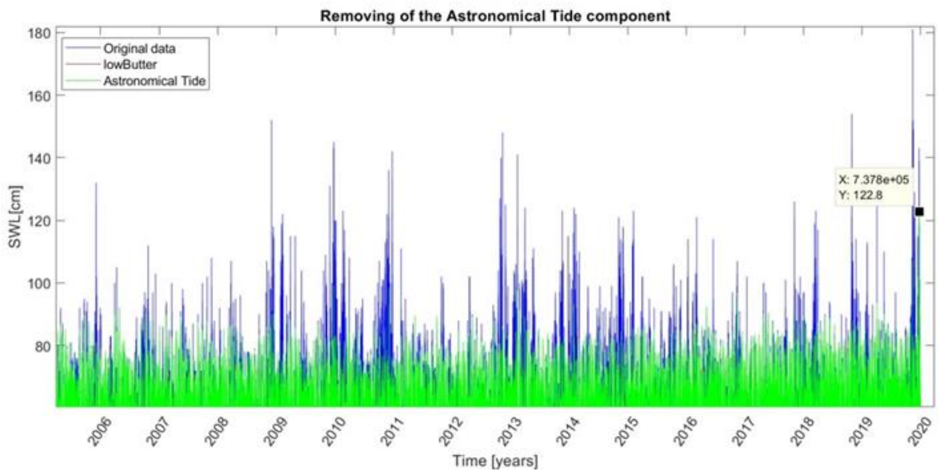


Figure 7 – Astronomical tide component from the data series at Punta de la Salute

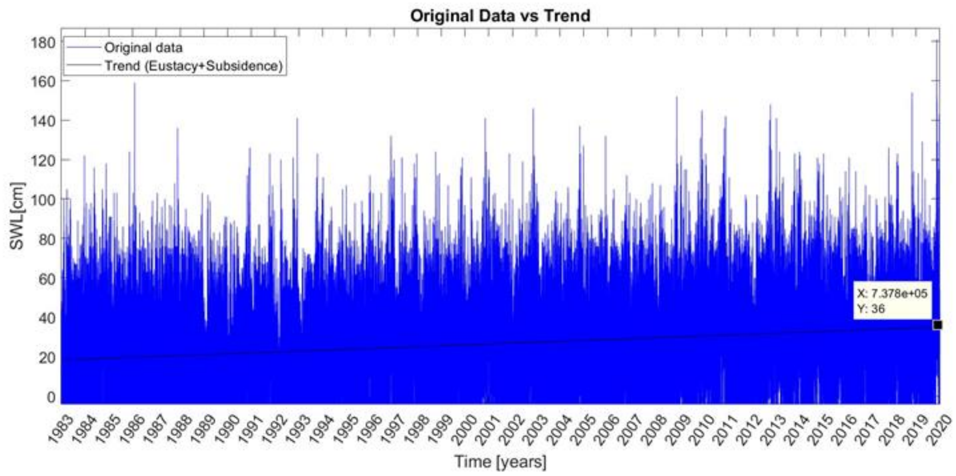


Figure 8 – Linear trend removed from the signal, acumulating a total of 35.178 (in figure sligtlhy differs due to matlab rounding).

The graphs above (actual observed data) differ significantly from the information displayed in Ferrarin, 2019. The maximum water level found in our data is 181 cm, the astronomical tide is 122.8 cm and the meteorological + SLR component of 58.2 cm (35.178 cm SLR + 23.02 cm of meteorological storm surge). The errors come from several possible sources. Firstly, the sample frequency used in our data is smaller than the frequency used for the Ferrarin analysis, therefore resulting in different maxima. Also, the water level data used has been detrended to account for subsidence and eustasy. Comparing the detrended data to observed water level data, which is not detrended to account for such phenomena, would logically produce some errors. Finally, the above meteorological residual data is the result of the filter analysis subtracted from the raw data.

The meteorological phenomena that resulted in the 12 November event are recorded below.

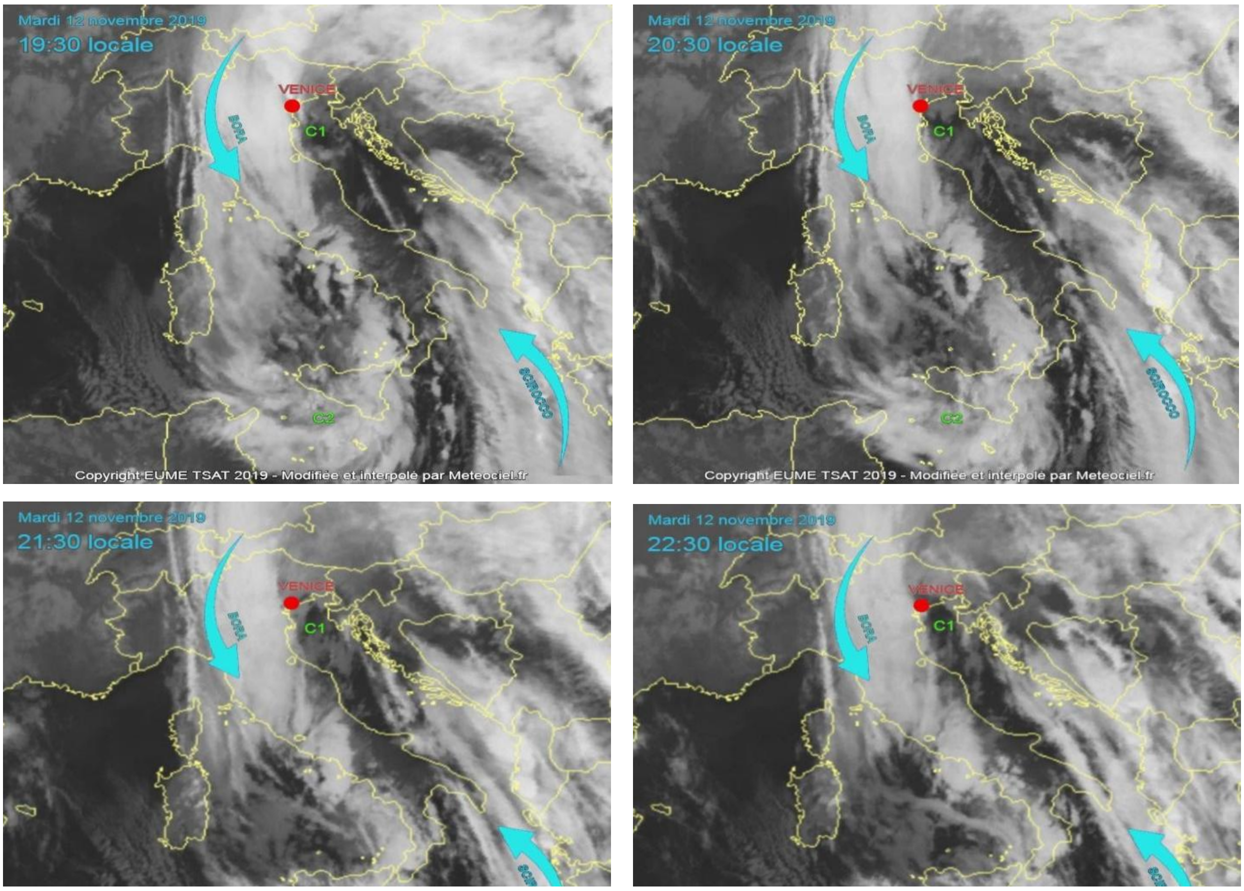


Figure 9 - Four satellite images of the atmosphere above Italy taken at hour intervals from 19:30 – 22:30 on 12 November 2019

Above: Four satellite images of the atmosphere above Italy taken at hour intervals from 19:30 – 22:30 on 12 November 2019. This interval was chosen to better visualize the development of the atmospheric phenomena that caused the water level peak at 22:50. The creation and progression of the cyclone above Venice (C1) as well as the progression of the cyclone in the South of Italy (C2) are both visible. The Bora (northerly) and Scirocco (southerly) winds are evident as well and highlighted with light blue arrows.

The meteorological (residual) data and the astronomical (tide) data for the October 2018 and November 2019 events are shown below for comparison. The resulting graphs succeed in providing insight to the general status of events at the time.

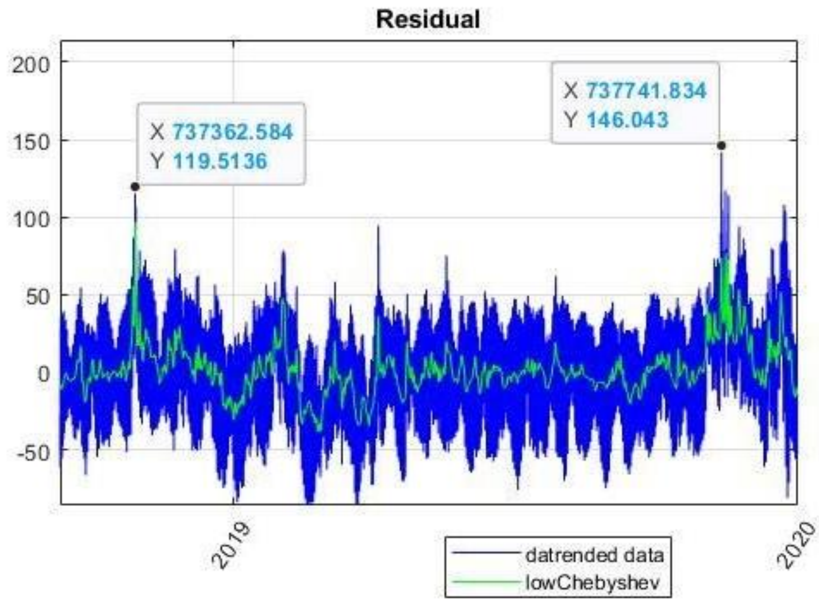


Figure 10 - The meteorological (residual) from the detrended data for the October 2018 and November 2019 events

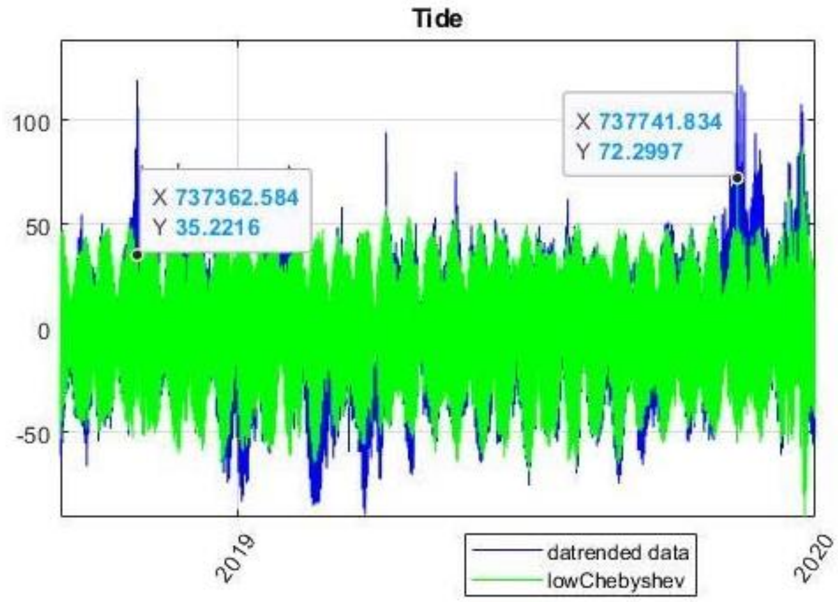


Figure 11 - The corresponding astronomical tide data for the October 2018 and November 2019 events

Both extreme water level events were caused by a sudden rise in the water level accompanied by a peak in the tide. The October 2018 event had a meteorological storm surge greater than the November 2019 event, but instead this meteorological storm surge occurred at a lower astronomical tide creating a lower intensity flood event.

.

While the 2019 event had a water level overpassed only by the 1966 event (i.e. second in the available historic data), it did not have even the second highest meteorological tide in history. However, the event occurred during an unusually high astronomical tide, which resulted in an exceedingly high water level.

Observing water level data on an hourly scale can offer a better understanding into extreme events, such as the November 2019 event and the October 2018 event. Further statistical analysis into the water level data over the course of several years better characterizes the Venice Lagoon and can be used to estimate the probabilities of the occurrences of certain water levels, which is done in the following section by means of previously published works.

3.4 Return Periods of Venice Lagoon

Statistics pertaining to the water levels in the Venice Lagoon and the Adriatic Sea were used to determine the frequency of certain water levels as well as the probability of such water level events occurring. The inverse of the exceedance cumulative probability of a water level event occurring is known as a return period, or the estimated time between events. Below is a table containing data related to estimated water levels for 2, 10, 50, and 100 – year return periods. These results were gathered using a joint probabilities method to reduce the number of assumptions poorly satisfied by many available tide-gauge records. The probabilities gathered from the literature review, of tides and surges were evaluated separately, and independence was assumed between these two processes. Then the probabilities found for both tides and surges were used to estimate the return periods for certain water levels in the Venice Lagoon and in the Adriatic Sea. These return periods were estimated by applying the probabilities to a generalized extreme value (GEV) model as well as the Gumbel theory of extreme values (Pirazzoli, Ullman, & Tomasin, 2007).

This method often results in overestimated return heights, or underestimated return periods, due to tide-surge interaction and neglect of seasonal effects on the tide. Although the potential errors in the results must be acknowledged and understood, the results succeed in providing a better understanding of the water level conditions in both the Venice Lagoon and the Adriatic Sea. These return periods were found by researchers at the Italian Consiglio Nazionale delle Ricerche (CNR, *Lit. National Research Council*) using water level data provided by the Municipality of Venice. The data corresponding to Diga Sud Lido was collected from 1968 – 2005 and the data corresponding to Punta della Salute was collected from 1940 – 2005 (Pirazzoli, Ullman, & Tomasin, 2007; Brambati, Carbognin, & Quaia, 2003). Diga Sud Lido is a station in the Adriatic Sea while Punta della Salute is in the Venice Lagoon.

Table 2 - Estimation of Return Periods for Water Levels (cm) of Venice Lagoon (taked from Pirazzoli, Ullman, & Tomasin, 2007).

Station	Estimated return level and 95% confidence intervals based on a GEV model for return times of:				Resulting largest heights (cm) from the Gumbel (1954) theory of extreme values for return times of:			
	2 yr	10 yr	50 yr	100 yr	2 yr	10 yr	50 yr	100 yr
Diga Sud Lido	100 (97-104)	119 (114-125)	131 (124-145)	135 (128-153)	102	129	153	163
Punta della Salute	100 (97-104)	122 (117-131)	131 (124-145)	149 (137-177)	100	124	146	155

The provided data suggests that the event that occurred on 12th November 2019 exceeded the estimated 100-year return period. A different source conducted similar analysis but for return periods greater than or equal to the 100-year return period (Fletcher & Spencer, 2005). Unlike the above chart, this data distinguishes the dominating winds occurring during the extreme water level event. This data is compiled in the graph below. Unlike Pirazzoli, only data from Punta della Salute was used. The time frame over which the data from Punta della Salute is calculated was also not specified. The data for this calculation was collected at Punta della Salute over an unspecified amount of time.

Table 3 - Flooding and environmental challenges for Venice (Spencer & Fletcher).

	Return Periods for Scirocco-Dominant Events			Return Periods for Bora-Dominated Events		
	10 years	100 years	200 years	10 years	100 years	200 years
Surge peak level (cm)	115	175	210	119	160	185

There is some observable difference in the peak water level associated with the same return periods that differ between the two sources. This difference is likely the result of different methods of calculation. The data compiled by Pirazzoli explicitly uses two methods - Gumbel theory of extreme values and general extreme values models - but lumps together all the high-water level events without distinguishing whether the events were Scirocco- or Bora-dominated. In contrast, the data compiled by Fletcher separates the data into categories regarding wind dominance, but the method used to calculate these values is not explicitly stated. While the return period for 10 years varies only slightly, the differences in the calculated values increases with the higher return periods. Due to the geographical conditions of Venice, the maxima are mostly due to the Scirocco condition since Scirocco-dominated events tend to experience higher water levels.

This data can be used to estimate the return period of the November 2019 event, which was a Scirocco-dominated event. The event, which peaked at 187 cm, was compared to the return period data provided. To estimate the missing values in the respective data provided by Fletcher and Pirazzoli, the values were interpolated linearly as shown in Figure 12. Two important water levels – the November 2019 event peak surge (187 cm) and the Mo.S.E. barrier closure level (110 cm) were compared to this data to estimate the return periods for both events.

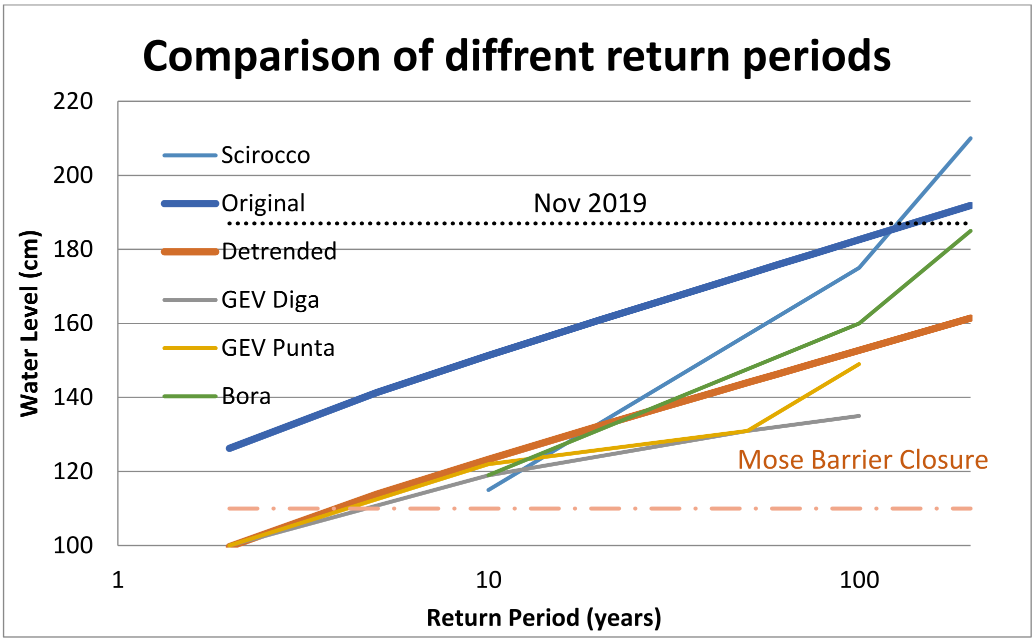


Figure 12 - Comparison of November 2019 Event and Mo.S.E. barrier closure level to existing return period data

There is noticeably a larger discrepancy in the data for the higher return periods (> 50 years) than for the lower return periods. This is likely the result of different calculation methods used to estimate the water levels with the higher return periods. Because these extreme events occur significantly less often than the much lower, more common water levels, their probabilities are harder to estimate accurately and will vary in different calculation methods. Also, it is important to mention that at Pirazollii et al., 2007, it is emphasize the data is manipulated to represent the water levels respect the MSL and not respect a datum, reason why the sea level rise and subsidence is already removed from the assessment of the extremes. Comparing from the current data return period assessment at Figure 12, we can see that all lines are closer from the "detrended" return periods.

The fact that the event was Scirocco-dominated is supported by the fact that the data falls within the range of values for Scirocco dominated events. Estimating the return period for the November 2019 event by analyzing the intersection in the above graph determines the return period that falls within the approximate range of 130 – 140 years.

The level at which the Mo.S.E. barrier is designed to close (110 cm) can be compared to this data as well. Compared to the extreme water level events of October 2018 and November 2019, this water level of 110 cm is very low and therefore has a much lower return period. As seen in the figure 15, the closure level falls between the 2-year and 10-year return periods. The varying data gives the closure level a 5 – 7 year return period range.

3.5 Hydrologic criteria pertaining to Mo.S.E. operation

The Modulo Sperimentale Elettromeccanico (Mo.S.E, *Lit. Experimental Electromechanical Module*) is a series of mobile barriers located at the three inlets of the Venice Lagoon, Lido, Malamocco, and Chioggia. The barrier is designed to close (lift up out of the water) before the water level measured at Punta della Salute reaches +110 cm with a return period of 5 – 7 years and open (lower back to the starting point underwater) when the water level outside the Venice Lagoon decreases to below +110 cm. Because the water is prone to rising at a rapid rate, the barriers cannot begin to close when the storm surge reaches +110 cm. Because the barriers take 30 minutes to close, it is imperative that the high water level is accurately predicted in advance to prevent the barrier from opening too late, which would lead to failure and thus flooding in Venice (NOVA, 2002).

The rate at which the water rises must be effectively determined well in advance so that the barrier can begin to open before the water level reaches 110 cm. In order to better estimate this rising rate, two classes and four subclasses have been determined. Along with these classes and subclasses, there is a corresponding water level at which the barrier must begin to rise so it can close before the water level in the lagoon exceeds 110 cm. The criterion to distinguish between each class was determined using a specific design storm with a return period of 10 years. This design storm has a storm surge of 150 cm and lasts for 11 hours. These classes are then further divided the four subclasses based on wind set-up in the lagoon, projected rainfall and inflow from surrounding watershed (Cavallaro, 2017). The classes are shown in Table 4.

Table 4 - Classes of operation and relative and relative water level (Cavallaro et al., 2017)

Class	Subclass		Closure Level (m)
Class 1 Return Period < 10 years Wind is <15 m/s	Class 1A	Rainfall < 1 mm/h Inflow < 150 m3/s	1.00
	Class 1B	Rainfall > 1 mm/h Inflow > 150 m3/s	0.90
Class 1 Return Period < 10 years Wind is >15 m/s	Class 1AV	Rainfall < 1 mm/h Inflow < 150 m3/s	0.80
	Class 1BV	Rainfall > 1 mm/h Inflow > 150 m3/s	0.75
Class 2 Return Period > 10 years	-		0.65

To determine when the barrier will close, the water level data as well as the meteorological data is very carefully monitored. The strength of the imminent conditions are then estimated well in advance and is then assigned a category. The Mo.S.E. barrier will then rise at the closure level corresponding to that category. The closure levels of the Mo.S.E. barrier are elaborated upon in section 5.4.2.

The existing sea water level data measured at Punta della Salute was analyzed to determine how many past water events occurred above the safe-guarding threshold of +110 cm. This was done by conducting a peak-over-threshold analysis, which extracts the number of peaks that occur above this chosen safe-guarding threshold. The peak-over-threshold analysis was performed on the Venice water level data from 1924 – 2015. The threshold assigned to this analysis is the safeguarding level of +110 cm and the number of peaks that exceeded this value were counted. This analysis was conducted by researchers at the University of Catania in Italy using data from 1924 – 2015 provided by the Istituto Superiore per la Protezione e la Ricerce Ambientale (ISPRA, *Lit. Italian Institute for Environmental Protection and Research*).

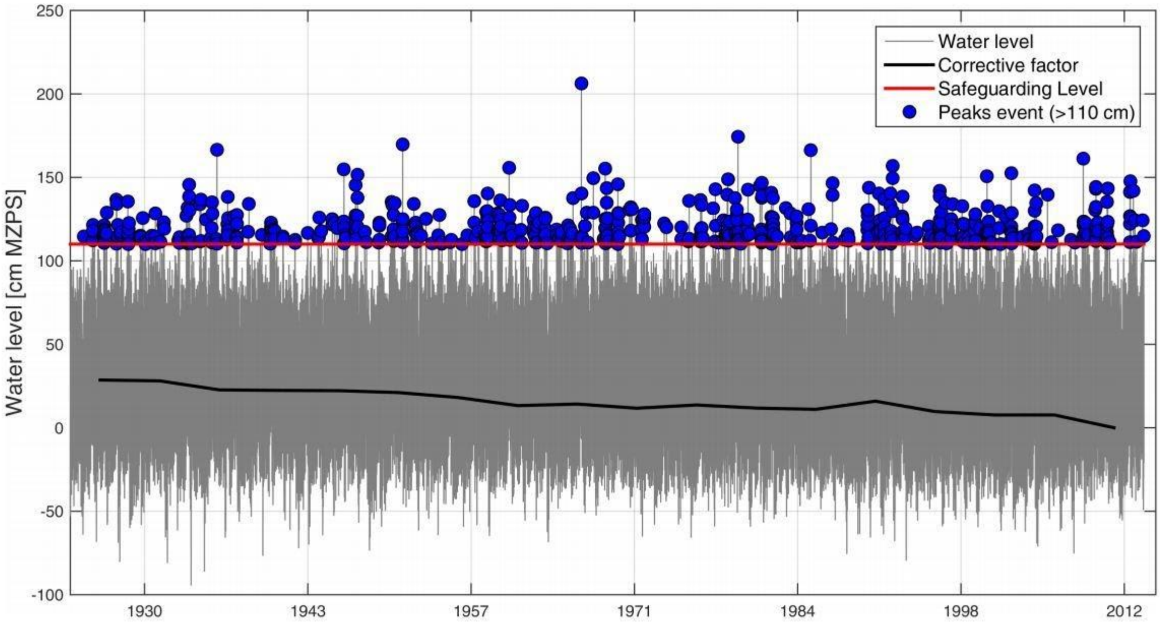


Figure 13 - Peak-over-threshold analysis (Cavallaro et al., 2017)

The analysis resulted in around 600 events characterized by water levels exceeding the chosen safeguarding threshold of +110 cm measured at Punta della Salute. These events were then sorted based on the height of these extreme events. The peaks determined from the previous peak-over-threshold analysis were sorted into different 10-cm intervals to visualize the frequency at which these events occur, in Figure 14.

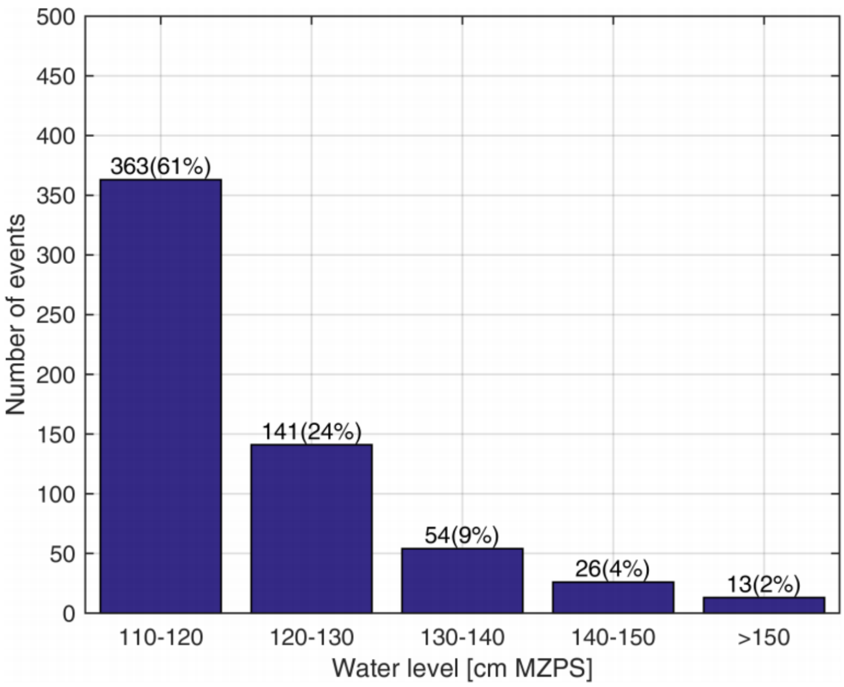


Figure 14 - Frequency at which high peak events occur

Of the 600 events that exceeded the safe-guarding threshold of 110 cm, 61% fell into the 110-120 cm range while only 2% exceed 150 cm. This 2% accounts for storms with return periods of 50 – 200 years. The 600 events over the course of 91 years averages to about 7 extreme water level events per year.

Using the above criteria, the 1966 event as well as the Scirocco- and Bora-dominated design storms were classified based on the characteristics of the event. Characteristics such as closure duration, level of lagoon at the time of closure, and maximum water levels in the lagoon were estimated as well.

Table 5 - Classification of 1966 event, along with Scirocco ad Bora-dominated design storms (Fletcher & Spencer, 2005)

Storm Surge Event	1966 event	Scirocco Return Period		Bora Return Period	
		100 years	200 years	100 years	200 years
Surge peak level (cm)	194	175	210	160	185
Closure Duration (hours)	24	20	24.3	10.1	11.0
Class	2	2	2	2	2
Closure level (cm)	65	65	65	65	65
Max. Level at Venice (bm)	102	97	103	70	75
Max. Level at Chioggia (cm)	96	89	97	104	108

The November 2019 high water level event would have been classified as a Class 2 event due to winds stronger than 15 m/s (winds at 27.75 m/s were recorded on 12 November) and a storm with a return period greater than 100 years. Therefore, the Mo.S.E. barrier would have started closing at 65 cm to prevent flooding in Venice during such an event. The Mo.S.E. opens again after the water level descends to below 110 cm. Below is the water level data from the 12th November event with an estimation for the duration of the barrier closure, if the Mo.S.E. were functional at the time. The 12 November 2019 event was analyzed for peak events to determined when the Mo.S.E. barrier should close and for how long it should be closed for. The data given for the event determined that the event should be categorized as a Class 2 event. Therefore, the Mo.S.E. barrier would have closed at 65 cm and reopened once the water level fell below 110 cm again as illustrated in Figure 15.

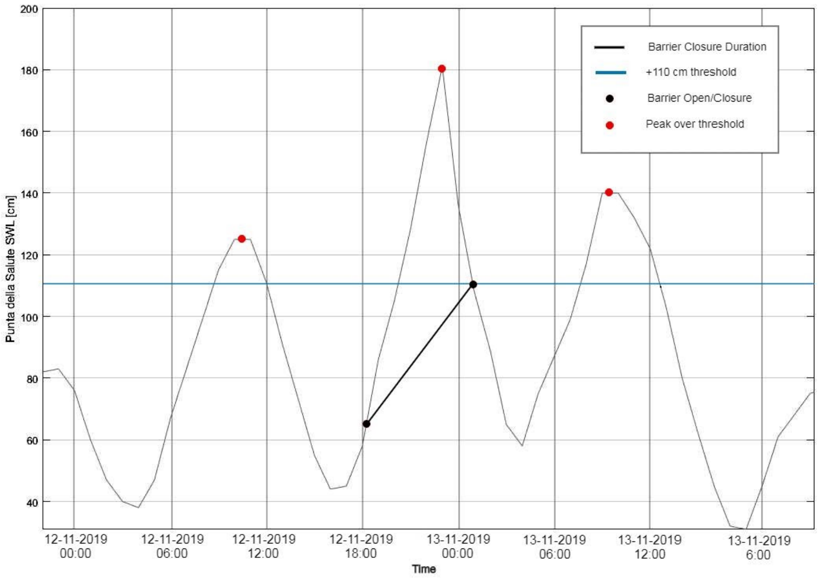


Figure 15 - Barrier closure duration estimation.

If the MO.S.E. barrier was functioning on 12 November 2019 and been closed at 65 cm and open again at a descent level below 110 cm, probably Venice would not had suffered the big impacts it has. If the barriers began to raise above the water when the water level reached 65 cm, the barriers would have fully closed in thirty minutes if the design functioned properly. It is therefore possible that the peak water level within the Venice Lagoon could have been even lower than 110 cm if the barrier closed in time. The barriers would have lowered once the water level in the Adriatic Sea fell below 110 cm, and therefore would have been raised for 7 hours.

This time estimation was assumed only for the prevention of the peak water level occurring at 22:50 on 12 November. The water level data for the November 2019 event indicates more than one instance where the water level peaks at above the safeguard threshold, signifying that the barrier would have to open multiple times during this period. However, because these peaks are significantly lower than the 12 November peak, it would not be necessary for the Mo.S.E. to begin closing as early as a water level of 65 cm and the durations would be shorter. If the Mo.S.E. barrier were to remain closed to prevent all three peak water levels in one closure duration, the closure duration in such an instance would have been approximately 30 hours.

3.6 The influence of climate change on return periods

As introduced previously, relative sea level rise threatens the safety of Venice in the present day. The combination of sea level rise and the sinking of Venice itself magnifies the threat of flooding posed by both effects. The increase in the sea level would therefore directly result in an increase in the frequency of extreme water level events.

Many sources differ on the exact estimated sea level rise that is projected to occur by 2100. Some projections predict a sea level rise ranging from 30 cm to 100 cm, whereas other empirical models estimate a rise of up to 175 cm (Umgiesser, 2019). Because the estimated rises in sea level vary so wildly, the related changes in return periods vary greatly as well. Due to both global eustasy and the sinking of Venice, certain water level heights will become more common and have a smaller return period than previously.

A study conducted an analysis of the potential changes on the return periods for water levels within the Venice Lagoon (Lionello, Galati, & Elvini, 2010). This study considered three scenarios. The first scenario is the control scenario (CTR) and assumes that the rate of sea level rise matches the pattern of the existing water level data. The water level data pertaining to CTR reproduced conditions from 1961 - 1990. The second scenario, A2, assumes higher emissions and therefore a faster rate of sea level rise, whereas the third scenario, B2, assumes lower emissions and a lower rate. Both A2 and B2 cases explore future scenarios and are meant to represent the projected return periods for the water levels from 2071 – 2100. The analysis of the data determined the projected storm surge height and the sea level of the three scenarios: the control scenario (CTR, the height emission scenario (A2), and the low emission scenario (B2). The dashed lines represent the standard deviation of uncertainty as a function of the return period for all three scenarios. In both the graphs in Figure 16, the x-axis denotes the return period and the y-axis denotes the surge height in centimeters.

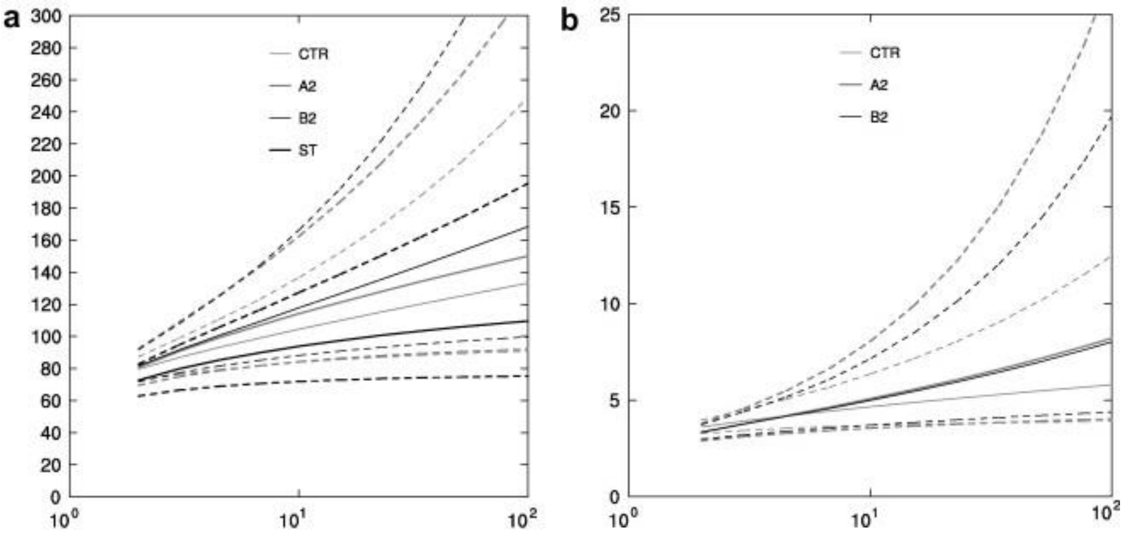


Figure 16: Projected storm surge height and sea water level of the three scenarios CTR, A2, B2

The above analysis resulted in new calculated water levels associated with certain return periods, most distinctly the 10-year and 100-year return periods. The results of the study suggested that the low-emissions scenario (B2) would result in a higher frequency of extreme water level events than the high-emissions scenario (A2). The study also resulted in a high standard deviation range for both the CTR, A2 and B2 scenarios. This is because of the large level of uncertainty resulting in different models projecting different expected sea level rises for the next century. However, the scenarios generally agree that both low-emission and high-emission climate change scenarios will result in more frequent high water level events as well as an increase in the water levels associated with both the 10-year and 100-year return periods.

The data has been compiled and compared to the return period and standard deviation range found for the Adriatic Sea and the Venice Lagoon in Section 3.4. The results are shown in Table 6. Please note that the estimated future return period data was made using water level data collected in the Diga sud Lido station in the Adriatic Sea from 1971

– 1990 and the return period data for both the Adriatic Sea and the Venice Lagoon was collected using data from Diga sud Lido and Punta della Salute, respectively, from 1940 – 2005.

Table 6 - Future projections (A2 and B2) for 10-year and 100-year return period for the Adriatic Sea was created using data from 1971 – 1990 (Lionello, Galati, & Elvini, 2010)(A2), (Pirazzoli, Ullman, & Tomasin, 2007)(B2)

	Estimated Storm Surge Level (cm) and Standard Deviation Range Associated with Certain Return Period	
Data Set	10-year Return Period	100-year Return Period
CTR (control)a	100 (80 – 130)	135 (90 – 250)
A2 (high-emission future)a	110 (85 – 150)	140 (90 – 300)
B2 (low-emission future)a	115 (85 – 160)	165 (100 – 300)
Adriatic Sea Datab	119 (114 – 125)	135 (128 – 153)
Venice Lagoon Datab	122 (117 – 131)	149 (137 – 177)

The data used to calculate the results for both studies differ significantly. Although both studies use the CNR research platform Diga sud Lido located in the Adriatic Sea, the range for the future prediction data is much smaller than the range used to calculate the current return period. This range for the latter calculation also uses more recent data, which takes into consideration the sea level rise for an additional twenty more years than the data used to calculate the future predictions.

Despite this difference, the data for future projections is quite close to the current accepted return periods. However, the future return periods were meant to represent water levels much further into the future. Although this may initially suggest that sea levels are rising faster than anticipated, it is more likely that this phenomenon is due to the wide range of uncertainty and the limited data set considered when calculating the future return periods. It is this uncertainty that produced the wide range in the standard deviation of these calculations. Because these predicted sea levels have already been reached, further sea level rise and an increase in the frequency of high water level events can still be anticipated.

The current accepted return period range and the future anticipated return period range by the end of the 21st century for both the Mo.S.E. barrier closure level and the 12 November 2019 peak water level are compared in Table 7. These future return periods were estimated using the data range provided in the study conducted by Lionello et. al.

Table 7 – Comparison of Return Period Ranges for Mo.S.E. Closure Level and 12 November 2019 Peak Water Level (Lionello, Galati, & Elvini, 2010)

		Estimated Return Period Range (Years)	
	Water Level (cm)	Current	Future
Surge peak level	187	130 – 140	50 – 100
Mo.S.E. barrier closure evel	110	5 – 7	2 – 5

Comparing the water level data to the estimated future return period ranges resulted in the return period range for the November 2019 event decreasing from 130 – 140 years to 50 – 100 years, and the Mo.S.E. barrier closure level range decreasing from 5 – 7 years to 2 – 5 years. These ranges are larger than the previous ranges due to the uncertainty of the data used to calculate the future return periods. Many factors influence the rate of sea level rise, so an accurate estimation is difficult to make. However, the data suggests that these water levels will certainly increase in frequency.

3.7 Conclusion

Analyzing the sea water level and related statistics for the Venice Lagoon has provided a more in-depth understanding of the factors considered while designing the MO.S.E. barrier. The water level of 110 cm was determined using the water level associated with a 10-year return period for the Venice Lagoon data. Statistical analyses also provided insight into the water levels for the 50-year, 100-year, 150-year, and 200-year events. The given data related to the Mo.S.E. design indicates that the barrier was designed to close at a level of 110 cm, but the water level at which it will start to close is dependent on a storm classification system designed around a design storm with a 10-year return period. By this classification system, the 12 November 2019 event would have been categorized as Class 2 and therefore the Mo.S.E. barrier would have had started to rise when the water level was at 65 cm at around 18:05 on 12 November 2019. It would have stayed in the raised position for about 7 hours before once again lowering after the water level lowered to below 110 cm.

Furthermore, climate change is expected to result in an increase in the sea water level as well as an increased frequency in extreme water level events. A low-emissions scenario anticipates a 10-year return period water level of 115 cm and a 100-year return period water level of 165 cm, while a high-emissions scenario anticipates a 10-year return period water level of 110 cm and a 100-year return period water level of 140 cm in the Adriatic Sea. Using data from the same study, it can be estimated that the range of return periods for the 12 November 2019 event will decrease from 130 – 140 years to 50 – 100 years, while the return period range for the Mo.S.E. barrier closure level will decrease from 5 – 7 years to 2 – 5 years. This study predicted these return periods for water levels by the end of the 21st century, but a more current study using a larger range of data suggests that this level has already been reached in the Adriatic Sea. Regardless, the sea level is still expected to rise due to climate change, as will the frequency of extreme water level events.

Although it is understood for what criteria the Mo.S.E. barrier was designed, this does not change the fact that the Mo.S.E. barrier is still not complete and therefore cannot prevent current storm surges from affecting the City of Venice. For this reason, the statistical analysis of the November 2019 event as well as an in-depth analysis into the causes of the phenomenon provides a more well-rounded understanding of the many factors that must be considered for the future working barrier to be closed. Knowing the statistics behind the hydraulic conditions of Venice also helped confirm that similar future events can be prevented with the current barrier design.

Chapter 4: Impact and Damages

Bram Deuss (Section 4.7: Bram Deuss, Sandra Fatorić)

4.1 Introduction

The flooding of a historically significant city like Venice can have a large impact not only on the inhabitants and local society, but also on the buildings and structures within the city itself. In this chapter, the impact of the flooding of Venice in November 2019 will be assessed. The overall impacts on the city and its inhabitants will be considered, but the focus will be on the resulting damages of the buildings. Since the historic city center of Venice contains many buildings and structures classified as UNESCO cultural heritage sites, damage to these sites will receive special attention.

Initial information about the impacts was gathered by performing online literature and news article research. Information was also gathered by using a model that estimated flooded areas and the damages that resulted from the flooding. This model is created for the purpose of this fact-finding report. Therefore, the following research questions will be evaluated:

- What areas were flooded during the 2019 flood event and what were the water depths?
- What were the priced and unpriced damages as a result of the 2019 flood event?
- What have been flood prone areas in the past?
- If the barrier would have worked, how would it have affected the water levels and the damage?

The answers to these research questions will be found by building a model with which flooded areas can be determined as a function of the water level. This model will help in making estimations for damages as a result of the November 2019 flood event. The priced and unpriced damages will also be investigated by an online literature and news article research.

The structure of this chapter is as follows. First, the information resulting from the online literature and news article research will be given. Secondly, the functioning of the flood and damage estimation model will be explained. This is followed by the results of a research performed by using this model. Lastly, the results will be summarized and concluding remarks will be given.

4.2 Online literature and news articles

Initially, it is important to get some insight in what happened during the November 2019 flood event and what the impact of that flood event was. In this section, the information gathered by an online literature and news article research is given in a narrative manner. The following topics are discussed: the flood event, the flooded area, the impact of the flood event, the resulting damages overall, damages to cultural heritage, how the November 2019 flood compares to earlier flood events, trends in the flooding and local measures taken in response to the flooding.

4.2.1 The flood

Venice has been prone to flooding in the past. Minor floods occur approximately 4 times per year and major floods occur approximately once every 4 years (The Sun, 2019). In 2019, Venice was hit again by a large flood. The complicated causes of the event are described in Section 3.3. An extreme high tide inundated more than 80 percent of Venice on 12 November to 13 November (NBC News, 2019). The waters in Venice peaked at 1.87 m, the second highest water level in recorded history. Since official records began in 192, the water level in Venice been higher than 1.87 m only once, reaching 1.94 m in 1966 (BBC News, 2019).

The Italian government declared a state of emergency for the city on 15 November, three days after the water level reached 1.87 m (The Art Newspaper, 2020). The threat continued until 16 November, as the city experienced another flooding with a water level that reached over 1.22 m. The water level remained high over the course of the next week (NBC News, 2019) and according to locals the high water levels continued even up until 23 December (Cranley, 2019).

Not only the city center was flooded. The barrier islands Lido and Pellestrina have also been badly hit by the flood. The situation in Pellestrina was critical because the water had overwhelmed the sea walls (The New York Times, 2019).

4.2.2 Flooded areas

On the official Mo.S.E. website, information is available about the flooded area of the city center of Venice per water level (CVN, 2020). On the website, plots of the flooded areas are available at specified water levels. An example of such a plot is shown in Figure 17Figure 17. The water level of this plot is 1.9 m, which is the plot closest to the 1.87 m water level available. According to this plot, 88% of the area is flooded at a water level of 1.9 m

Figure 17 - Flooded area at 1.9m (Ministry of Infrastructure and Transport, 2020)

The percentage of the area of Venice that was flooded differs slightly per source. For instance, the BBC reports that 90% of Venice is already flooded at 1.4 m (BBC News, 2019), which varies from the information available at the Mo.S.E. website. This is probably because each source defines a different reference area. It is important to consider whether such sources only look at the city center islands (like in the case above) or if they also consider other areas, such as the barrier islands.

The flooded areas and percentages of the area flooded can be estimated with the model, which is elaborated upon in Section 4.8. Since the research areas are defined, the flooded percentages are clearer.

4.2.3 Impact

Floodwaters pushed boats ashore and swept through buildings. As a result, schools and supermarkets closed and a city council meeting was canceled. Residents and tourists had to navigate through the streets in waist-high waters (Risk Management Monitor, 2019).The flood also sank at least three vaporetti, which are public transportation boats used in Venice (The New York Times, 2019).

A major problem is the city sewers, which also function as drainpipes that carry off the rainwater. These drainpipes carry untreated sewage, including laundry suds and toilet effluent, into the canals which then carry the water into the lagoon, where the tides periodically flush it out to sea. During especially high tides, the drains carry the effluent onto the walkways of the city (Hyndman, 2009), posing a significant health risk.

The flood resulted in two fatalities. One man in his 70s died from electrocution as he tried to turn on a pump in his home (The Verge, 2019). A body of another man was found in his home (The Guardian, 2019). Both fatalities were on the island of Pellestrina (BBC News, 2019).

4.2.4 Damages

The November 2019 event was the worst flood to hit Venice in 53 years, causing €360 million worth of damage to public property. The estimate is based on an initial survey of repairs needed for jetties, paved areas, street lighting and buildings owned or managed by the municipality, including the civic museums (The Art Newspaper, 2020).

By the end of January, Individuals and businesses submitted around 7,200 compensation claims to the city administration for a total of €93 million. Following the November floods, Italy's government released €20 million in emergency relief. Private individuals should receive up to €5,000 and businesses up to €20,000 (The Art Newspaper, 2020).

Venice Mayor Luigi Brugnaro has said that damage costs could run as high as €1 billion (DW, 2019).

4.2.5 Heritage

After the flooding through Venice's 923-year-old St. Mark’s Basilica, it is believed that the iconic site suffered an estimated minimum of €5.5 million in damages. Floodwaters damaged the basilica’s underground crypt after floodwaters submerged the area for about 24 hours. The tiles of the Basilica’s dome were blown away by fierce winds. For the first time in the basilica's history, floodwaters came rushing through its windows. The basilica was closed for about a week for washing and minor repair damage (Travel and Leisure, 2019).

Salt from the lagoon waters, rather than the water itself, causes the most damage to the basilica as well as other old buildings. As saltwater flowed into the basilica, the salt seeped into the church's marble columns. The salt is also eating away at mosaics and the church's stone, brick and mortar foundations. Even at a height of 12 meters, crystallizing salt comes out (Travel and Leisure, 2019). The sea salt and the toxic substances found in the water, like feces and chemicals, also cause damage. Mold spreads quickly in and on moist walls as well (DW, 2019).

Venice's office for ecclesiastical cultural heritage has approved 85 applications to restore liturgical activities in churches around the city. Some were flooded for more than 72 hours consecutively, causing water to erode the underlying subsoil at churches including San Geremia, San Fantin, San Moisè and Sant'Agnese, and the ancient basilica on Torcello island—the oldest structure in the Venice Lagoon, dating back to the 7th century A.D. The costs of simply reopening the churches for worship have been estimated at around €1.5 million. However, to tackle some of the problems that have emerged due to the flooding, at least €4.5 million is needed. Fortunately, there was no serious damage to art works inside the churches.

The library and archives of the Venetian Benedetto Marcello Conservatory and Ca' d'Oro, a 15th-century palace museum on the Grand Canal, have been damaged by the flood. By 4 February 2020, Venice had raised €500,000 for the 12 November flood. Half of this has already been allocated to the Ca' d'Oro, the Venice Conservatory and ten churches (The Art Newspaper, 2020).

The SaveVenice Organization is funding cultural heritage recovery at the following churches: Santa Maria Assunta on the Island of Torcello, Santa Maria dei Carmini, Santa Maria del Giglio, Santa Maria dei Miracoli, Santa Maria Gloriosa dei Frari, Santi Apostoli, San Moisè, San Polo, San Sebastiano, San Stae. It is also funding the recovery of the following public buildings: Conservatorio Benedetto Marcello in Palazzo Pisani, Fondazione Giorgio Cini, Galleria Giorgio Franchetti at the Ca' d'Oro, the Jewish Cemetery on the Lido, Fondazione Querini Stampalia, Scuola Dalmata di San Giorgio degli Schiavoni, Scuola Grande di San Giovanni Evangelista (Save Venice, 2020).

4.2.6 Local measures

There are some measures that locally are being taken or investigated to mitigate the impacts of flooding.

A gangway made of wooden planks is put in place to assist pedestrian circulation when a water level of 1.2 m is reached (wikiwand.com, 2020). Also, regular dredging of the canals decreases the impact of rising water levels (The Guardian, 2015). Very few people in Venice live on the ground floor because of the humidity and the threat of flooding (BBC News, 2003) (Hyndman, 2009). Sandbags are also often used the prevent water from flowing in through canal-side windows in residential and commercial areas (CBS News, 2019).

In 1970, the local government prohibited the industrial pumping of groundwater in Venice to limit the subsidence of the city (Hyndman, 2009).

A group of geomechanical engineers from the University of Padua proposed that a restoration of the underground fluids via modern injection technology could actually raise the level of Venice. Optimistic projections indicate that Venice could be raised by 0.2 to 0.3 m through a large-scale injection project, a level that would counter the settling and subsidence of more than 0.2 meters since 1950. The group's plan called upon technology already used in the oil and gas industry to counter Venice's subsidence. Fluid pumping was initially considered in the 1970s, but the proposal was set aside because the technology to accomplish the task at that time was not economically feasible, and because some engineers feared that uneven rising could do more harm than good (encyclopedia.com, 2020).

4.2.7 Summary Priced and Unpriced Damages

According to the online literature and news article research, the priced and unpriced damages can be summarized as follows:

Table 5 - Priced and unpriced damages for the November 2019 flood event

	Priced	Unpriced
Direct	Houses, household effects and capital goods in total at least €93 million. Churches at least €9.5 million. Public property at least €360 million. In total up to €1 billion.	At least 7,200 victimized households and businesses. 2 fatalities. Footpaths in the historic center were obstructed. Damage to cultural heritage.

4.2.8 Relation to earlier floods

The largest water depths have been recorded during the flooding of Venice in 1966. The flood caused fatalities and a total damage of $1.1 billion. Adjusted for inflation, this amount is approximately worth $8 billion, or €7.3 billion (Forbes, 2019).

According to the Emergency Events Database (or EM-DAT), created by the Université catholique de Louvain in Brussels, Belgium, the 1.3 million people were affected by the 1966 flood and the event resulted in 70 casualties. Unlike different reports, EM-DAT estimates the total amount of damage at $2 billion at time. Adjusted for inflation, this is equivalent to the modern-day amount of $16.1 billion, or €14.7 billion. However, these numbers include the flooding of the Arno in Florence which happened at the same day (EM-DAT, 2020). This implies that this number is an overestimation of the actual damage. Similarly, the book *Changes in Flood Risk in Europe* reports $14 billion in damages as of 2012. Adjusted for inflation, this value is equal to about $16 billion, or €14.48 billion in 2020. However, this same source reports 113 to 118 fatalities (Kundzewicz, 2012).

The flood of Arno in November 1966 resulted in 101 fatalities, which means that about 12 to 17 deaths occurred in Venice (wikipedia.org, 2020). The total damage to Florence due to the flooding of the Arno was approximately $6.6 billion, or €6 billion, adjusted for inflation (The New York Times, 2016) and according to Arrighi et al., the damage to Florence was €6 billion in 2015 (Arrighi, 2015). Therefore, it can be estimated that approximately €8.2 billion to €8.4 billion in damages occurred due to the flooding in Venice.

Another major flooding of Venice occurred in 1986. This flood resulted in 2 deaths and a total damage of $20 million in 1986. Adjusted for inflation, this is approximately $47 million in 2020. During this flood a water depth of 1.58 m was reached (BBC News, 2008).

4.3 Flooded Area and Damages Model

Not all information required for this study is available on the internet and in news articles. For instance, the exact number of flooded buildings, or more specific information regarding the nature of the damage to building types, has not been found. News articles are also not always the most reliable sources. A possible method that could be used to gather more detailed and verifiable information is to make a model that can supply that information. Of course, such a model will never be 100% accurate and the result should be regarded as an estimation mainly to gain more insight into the magnitude of the impact due to a flood event. Therefore, a model was made with the intention of estimating the number of flooded objects, in this case buildings and streets, as a function of the water level. Based on this acquired value, the total damage due to the flooding of Venice in November 2019 was estimated. This same model could be used to evaluate the impact of other high water events in the history of Venice.

In this model, the water level elevation is compared with the elevation of the surface over the whole pre-determined research area. In this way, a raster of the city, which essentially functions as a map, can be made. This raster contains the water depths over the area. Using information pertaining to which objects are present in the research area, an analysis of the flooded objects can be made. This process is shown in Figure 18.

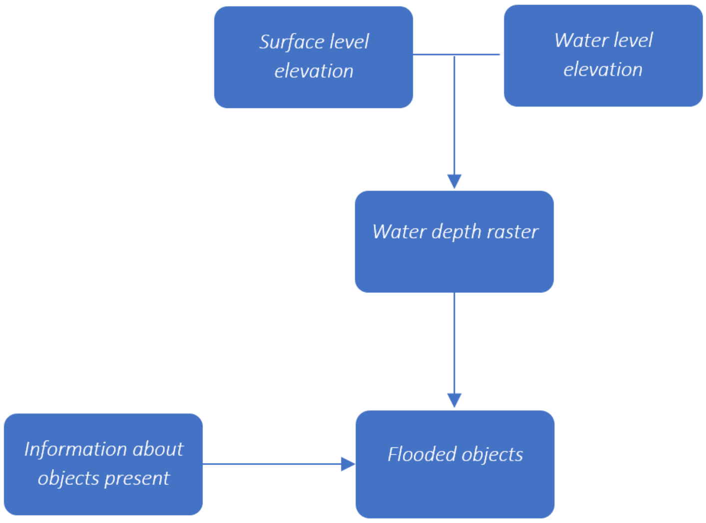


Figure 18 - Conceptual process of the model

Before the model can be effectively employed, the research area must be defined. During high water events, flooding occurs throughout many locations within the Venice lagoon. The area that was investigated is the area that has been prone to most floods. The research area comprises of the following sub areas:

- City center islands: the old city of Venice which contains the most cultural heritage.
- Lido: the northern barrier island.
- Pellestrina: the southern barrier island.
- Other islands: the remainder of islands throughout the lagoon.

The model separately assessed the flooded objects for these four areas. The subdivision of the research area made it possible to analyze the results focused specifically within the lagoon and thus the results have more meaning. In Figure 19, these sub-areas are shown.

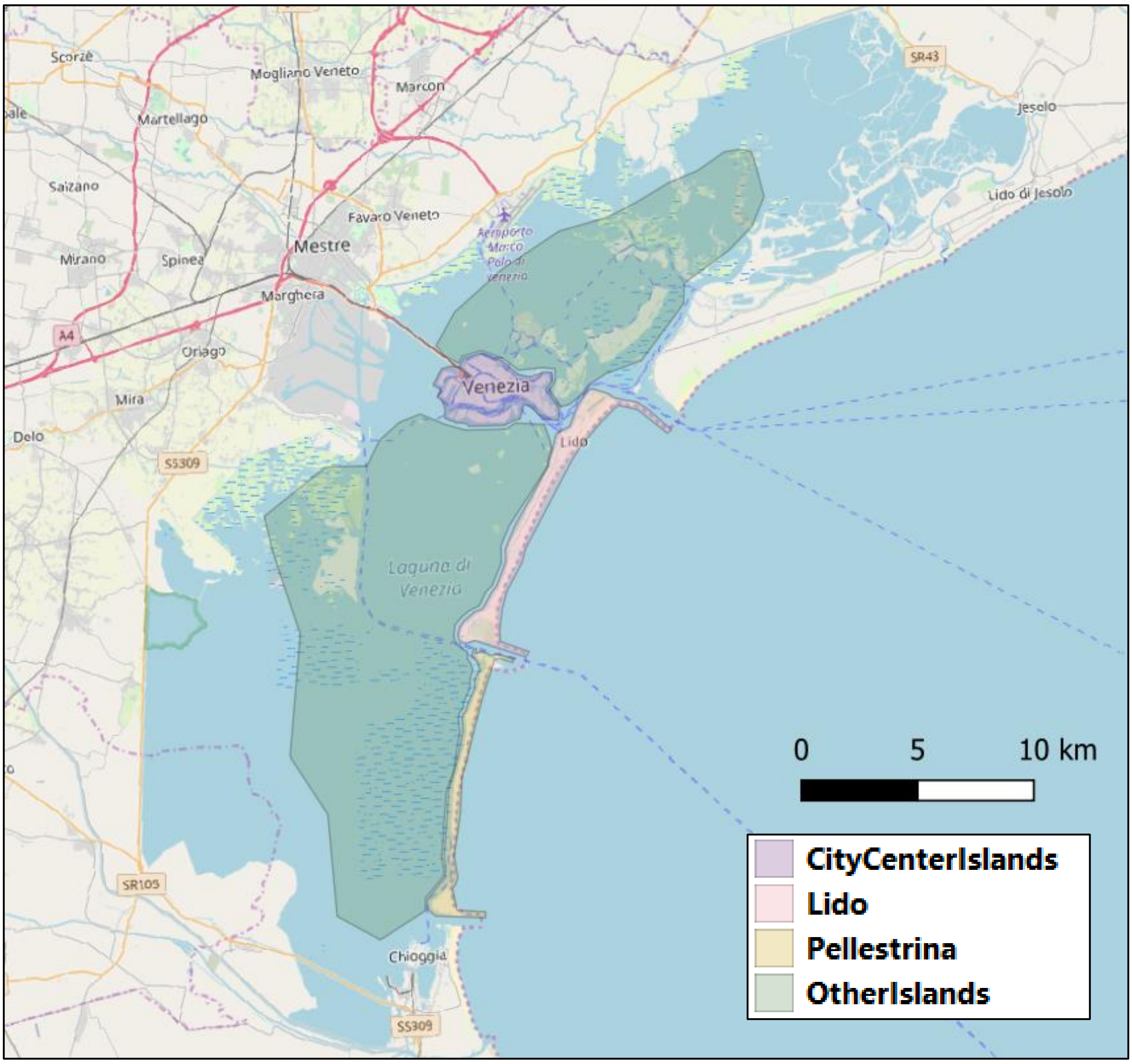


Figure 19 - Research area with sub-areas illuminated within the Venice lagoon

4.3.1 Bathtub Model

The model that was created to estimate the flooded area and damages is sometimes referred to as a “bathtub” model. This means that a certain water level is compared to the surface level elevation. If the chosen water level is higher than the surface level elevation at a certain location, the location is assumed to be flooded. If the water level at that location is lower than the surface level elevation, the location is not flooded.

Therefore, the bathtub model only considers the difference in elevation level between the water and surface. Dynamic influences, like horizontal velocity, inertia of the water and the roughness of the landscape on the water as it flows into a certain area are not considered by the model. As a result, the bathtub model usually overestimates the flooded area (T. Neumann, 2013). The principle of the bathtub model is shown in Figure 20.

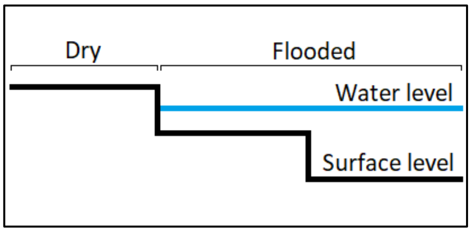


Figure 20 - Principle of the bathtub model

4.3.2 Surface Level and Water Level Elevation

Detailed information about the surface level elevation is not always available, which is necessary to achieve a high precision and reliability. In this study, surface level elevation data is used with a resolution of 5 x 5 m. This means that the elevation of the surface is constant over squares of 5 x 5 m (or 25 m^2). The surface level elevation data used is known as a Terrain Model (DTM). This means that the elevation data is given for the elevation level of the terrain only and excludes the elevation levels of higher objects such as buildings and trees. This is very useful for estimating the flooding at a location with a lot of buildings, such as the city center of Venice, since the elevation of rooftops would increase the average terrain level over a 25 m^2 cell and would decrease the accuracy of the bathtub model. However, this may also overestimate the amount of properties submerged by the flooding.

The DTM data is downloaded from Veneto Region's official website (Regiove Veneto, 2020). The reference level is the mean water level measured at Punta della Salute. The mean water level at this measurement station, located in Venice, is used as main reference level. Punta della Salute references the mean water level as it was in 1897 (venipedia.org, 2020). Due to sea level rise and the subsidence of Venice, this reference level lies approximately 0.34 m below the currently accepted mean water level (CNR, ISMAR, 2019). The DTM elevation data will be compared to the highest measured water level during the flooding of Venice in November 2019, which was 1.87 m above mean water level at Punta della Salute.

The DTM data is downloaded as an ASCII file. This means that each 25 m^2 elevation value is added in a text file from 'top left to bottom right,' separated by a space or tab. The first few lines of text give information about the number of rows and columns and the coordinates of the center of the top left cell.

4.3.3 Comparing the Data

The DTM was loaded into the numerical computing environment MATLAB as a matrix, so a comparison can be made with the water level. Each cell of this matrix represents a 25 m^2 elevation value. By using loops with conditional statements, the values in the matrix are compared with the 1.87 m water level. When the water level is larger than the surface level elevation, the difference is added to a cell with the same coordinates in a new matrix. Otherwise, a value of zero is added to the associated cell in the new matrix. In this way, a new matrix is created that shows a "0" if a cell is not flooded and shows the water depth if the cell is flooded.

The newly created matrix is saved as a text file. The same first lines of the DTM ASCII file that give information about the number of rows and columns and the coordinates of the center of the top left cell are added. In this way, the new matrix is then saved as an ASCII file. To illustrate this, the first few lines of the created ASCII file are shown in Figure 21.

```
ncols         7901
nrows         9110
xllcorner     1746920.000000000000
yllcorner     5010225.000000000000
cellsize      5.000000000000
NODATA_value  -999
 0.0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Figure 21 - Example of ASCII file

4.3.4 Geographic Information System

Since the newly created water depth matrix saves as an ASCII file, it can be loaded into a Geographic Information System (GIS). The software used in this case is QGIS, which uses the coordinates of the cells to show the information as a 'map'. In QGIS, information given by a matrix (in this case as an ASCII file) is called a raster. It is then possible to overlay the water depth raster with a map of the area and analyze where in the water depths in Venice occur.

The coordinates that are given in the downloaded DTM ASCII and are added to the water depth ASCII are not in the conventional latitude and longitude coordinate system. They are displayed in what is known as projected coordinates in a 'flat' cartesian-like coordinate system. More specifically, these coordinates are given in the EPSG:3003 projection, which is the optimized projection for north and west Italy. All other maps and data that can be loaded into QGIS must be translated to the EPSG:3003 projection. To get an idea of what the water depth raster values look like in QGIS, a sample raster at a water level of 1.87 m is shown in Appendix A.

4.3.5 Open Street Maps

The analysis of flooded buildings and structures is conducted by overlaying the water depth raster with information from Open Street Maps (OSM), an open source initiative of a world map in which everyone can add geographical information.

From Open Street Maps (openstreetmap.org, 2020) the following information is downloaded:

- Polygons: the outlines of all buildings and structures. Each polygon contains information about the building or structure it represents, such as the type, amenity, use and, in some cases, the name of the building.
- Points: the center points of all buildings and structures. Like the polygons, each point contains information about the building or structure it represents.
- Lines: all roads, highways, bridges, paths, etc. Each line contains information about the road it represents, like the street name and the type of the road.

The polygons, points and lines can be opened as separate layers in QGIS. When projected in EPSG:3003, it is possible to overlay the water depth raster and the OSM data. In Figure 22, the polygons, points and lines are shown overlaying the water depth raster respectively from left to right.

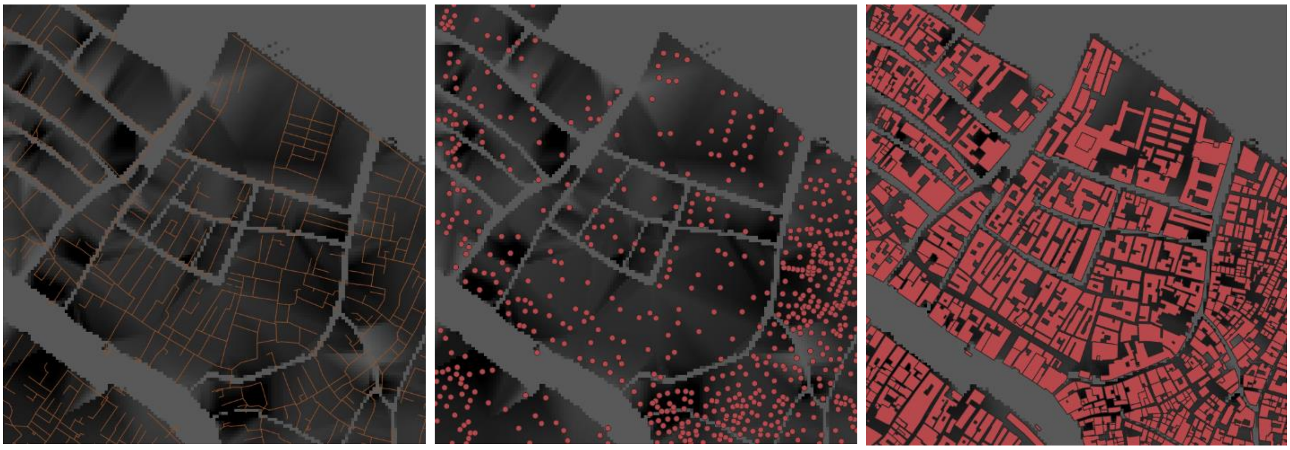


Figure 22 - From left to right respectively: Lines, points and polygons on overlaying the water depth raster

Ultimately, the choice was made to use only the information from the polygons and the lines. The points are not used since they mostly contain the same information as the polygons and analyzing them will not produce new useful information.

By drawing out the sub areas in QGIS, the OSM data can be clipped. This way, separate layers with polygons and lines are created for each sub-area, making it possible to analyze the flooded objects in each sub-area separately.

The program creates attribute tables that show all information pertaining to all polygons or lines. Each line in this attribute table is specific to one such polygon or line. These attribute tables show valuable information relevant to the specific raster. Therefore, these tables also provide the raster value, which in this case is the water depth, at the location of that certain building or road. For each sub-area, two such tables were created: one for the polygons, or buildings, and one for the lines, or roads, assigning a specific raster value for each.

The polygon or line can overlay more than one cell of 25 m^2. A mean raster value will be determined for each polygon and for each line. The total amount of cells that the polygon or line overlies is added to the table[2].

Information pertaining to bridges is not considered. Because most bridges cross canals, lines representing bridges cross raster cells with water depths that are distorted by the depth of the canal. Therefore, most bridges are registered as “flooded” by the bathtub model, even if this is not actually the case. This is inconsistent with reality as the bridges usually have a higher elevation than the roads and therefore would flood less often.

[2] Adding the mean raster value and the amount of cells to the attribute tables are both done with the plugin ‘v.rast.stats’ which is only available for QGIS with GRASS.

4.3.6 *Analysis of Results*

These tables are exported as .csv files and loaded into MATLAB so an analysis can be done. It is assumed that a polygon or a line is officially flooded if the ratio of the mean water depth to its area is larger than a certain predetermined threshold. This threshold is determined to prevent misleading information that could occur if an area is digitally flooded by only a few centimeters, as this usually does not cause significant damage in practice. Many windows and doorways are elevated by a few centimeters to prevent water from coming in up to a certain height. Therefore, flooding levels up to this specific height are not considered damaging.

The mean water level for each row is compared to this threshold by using loops with conditional statements. If the water depth is larger than the mean water level, then all information in the row is added to a new matrix. If the water depth is smaller, than the row is not added to the new matrix. The value of the threshold is defined in Chapter 4.4.

Through this process, two new matrices are obtained: one with information only about the flooded polygons and a second with information about the flooded lines. These two new matrices are made for each sub-area. With the new matrices, the following information can be obtained:

- The total amount of flooded objects.
- The total area of flooded polygons (buildings) and/or the total length of the flooded lines (roads).
- The mean water depth at all flooded objects.

The process of adding water depth values to the attribute tables and deriving information about flooded objects is schematically displayed in Appendix B.

The total amount of flooded objects is obtained by taking the number of rows in the matrix of flooded polygons or lines.

The total area of flooded polygons is obtained by multiplying the number of cells that each polygon overlies[3] by 25 m^2. Similarly, the total length of flooded roads is obtained by taking the number of cells that a line overlies and multiplying this by 5 m, resulting in a pragmatic estimation.

The value pertaining to the mean water depth at flooded objects is found in its own column in the matrix[4].

It is important to consider that numbers concerning the flooded number of objects and flooded areas of objects resulting from this model are likely overestimated. As previously explained, this is the case because bathtub models generally tend to overestimate flooded areas. Figure 23 shows a flow chart of the model to summarize and clarify the total process.

---

[3] As explained before, the amount of cells that each polygon or line overlies is added to the attribute table with the plugin 'v.rast.stats'.

[4] The mean water depth at flooded objects are, as explained before, obtained and added to the attribute table by the plugin 'v.rast.stats'.

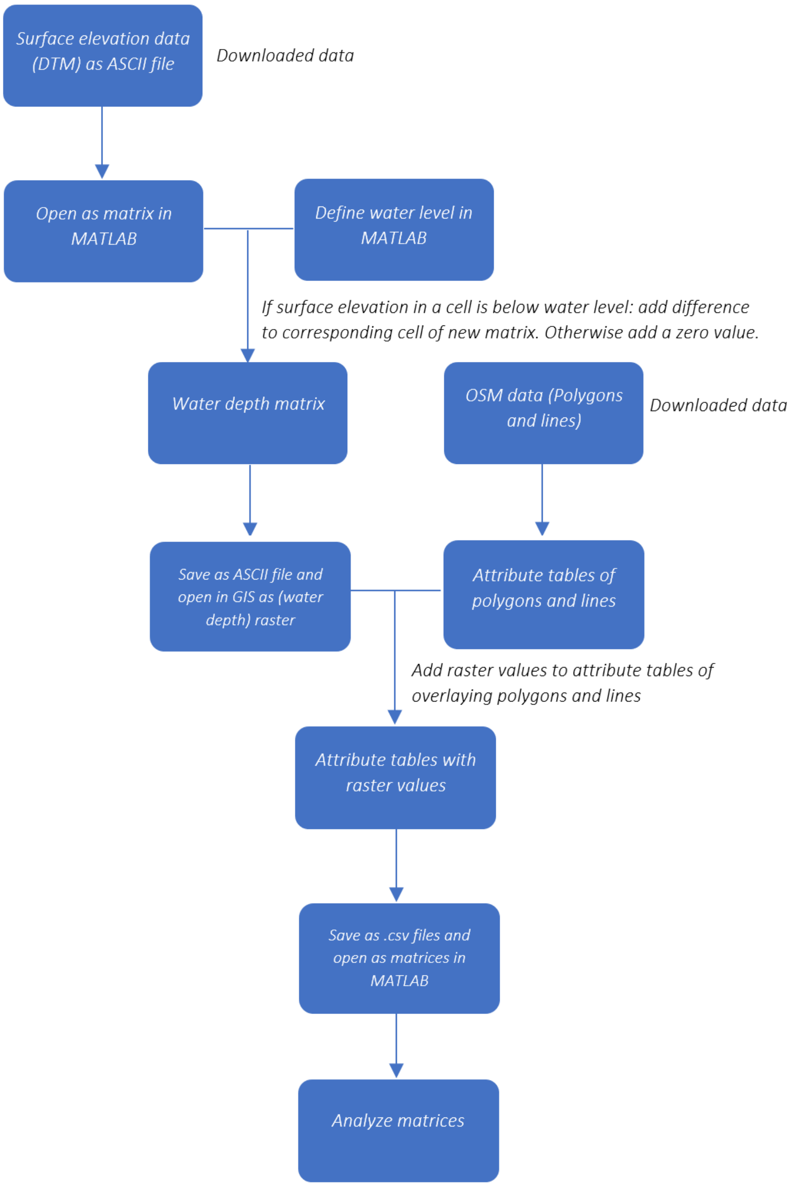


Figure 23 - Flow chart of the model

4.4 Validation of the Model

To better understand the reliability of the model, comparisons are made of situations for which information is available about the flooded area. A threshold of flooding is chosen that gives the most accurate results. As explained in Section 4.3, a threshold of flooding is necessary to define an extreme water level that does significant damage.

As mentioned in Section 4.2, Figure 24 shows the flooded area for the city center at a water level according to the Mo.S.E. website (Piano Generale degli Interventi, 2020) and the flooded area according to the flood estimation model, both at a water level of 1.9 m. This map is plotted without a specified threshold of flooding.

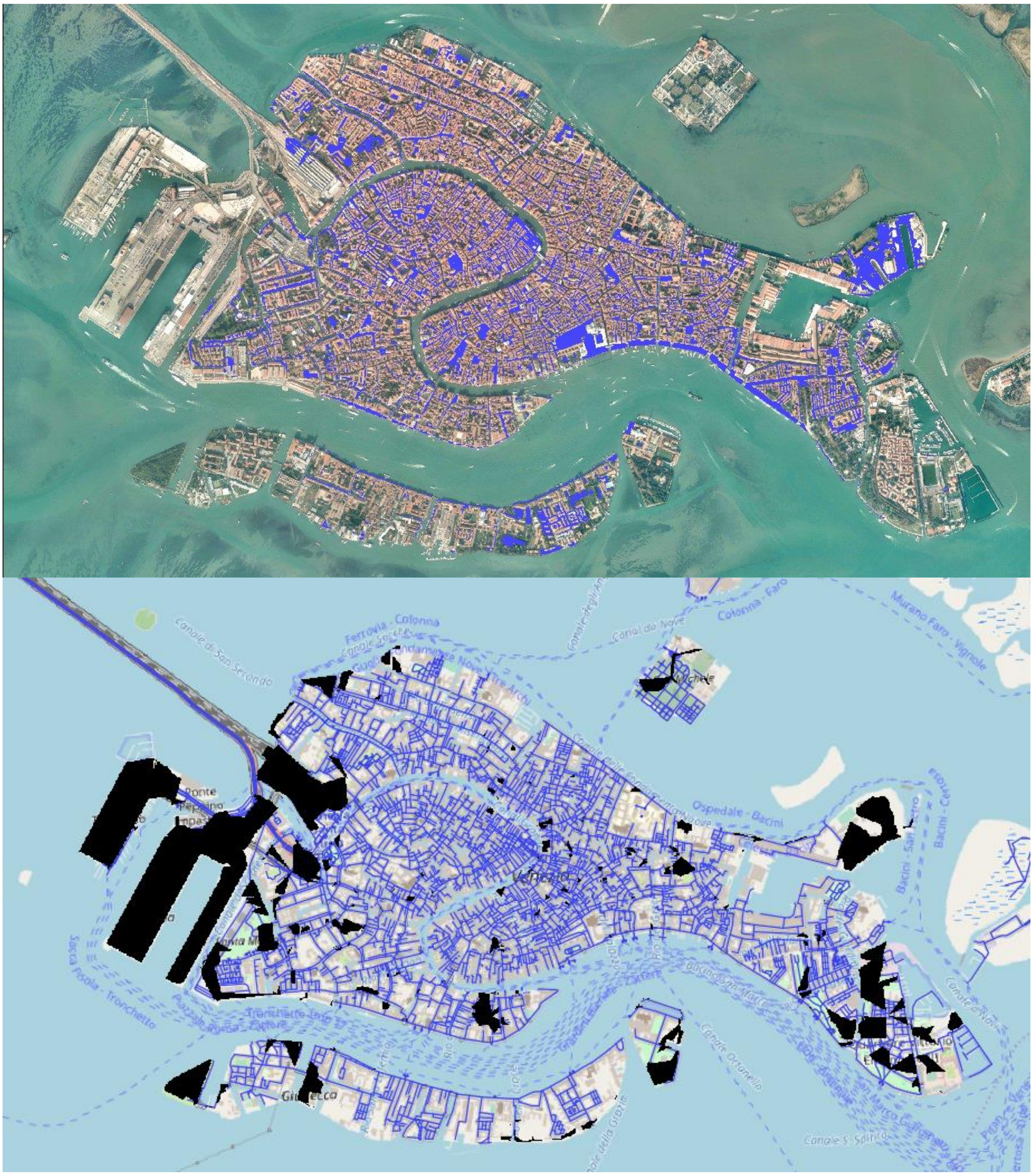


Figure 24 - Top figure: Flooded areas according to the MoSE website (Ministry of Infrastructure and Transport, 2020). Bottom figure: Flooded areas according to the model. The black areas are dry and the rest is flooded. The blue roads represent the flooded roads

Comparison of the two plots indicates that approximately the same areas flood in both models, indicating that the basic principle of the model works. However, it is important to acknowledge that the flooded areas of both pictures are not the same. The flood estimation model estimates a somewhat larger flooded area than the top figure does.

Venice stays virtually unaffected up until a water level of 0.9 m (Stravisi, 2011). Figure 25 shows the flooded areas at a water level of also 0.9 meter, according to the flood estimation model, still without a threshold of flooding.

Figure 25 - Flooded areas at 0.9m. The black areas are dry and the blue roads represent the flooded roads.

According to this model, some areas are flooded at a 0.9 m water level, indicating a slight overestimation of the flooded areas. This could be attributed to the fact that these two plots are made without a threshold of flooding. This lack of a threshold could result in a water depth as insignificant as 1 mm registering as a flooded area. Applying a threshold results in larger water depths required before an area is considered flooded.

Another factor is that the geographical information from the DTM data takes an average surface level elevation over every 25 m^2, neglecting possible walls and certain areas with a higher elevation that could possibly obstruct the water.

Increasing the accepted threshold of flooding could result in a more accurate model. After some iteration, a threshold of 0.3 m seems to give the most accurate results, in line with the information provided by various sources. The flooded at both 1.9 m and 0.9 m including a threshold of 0.3 m are shown in Figure 26 and Figure 27.

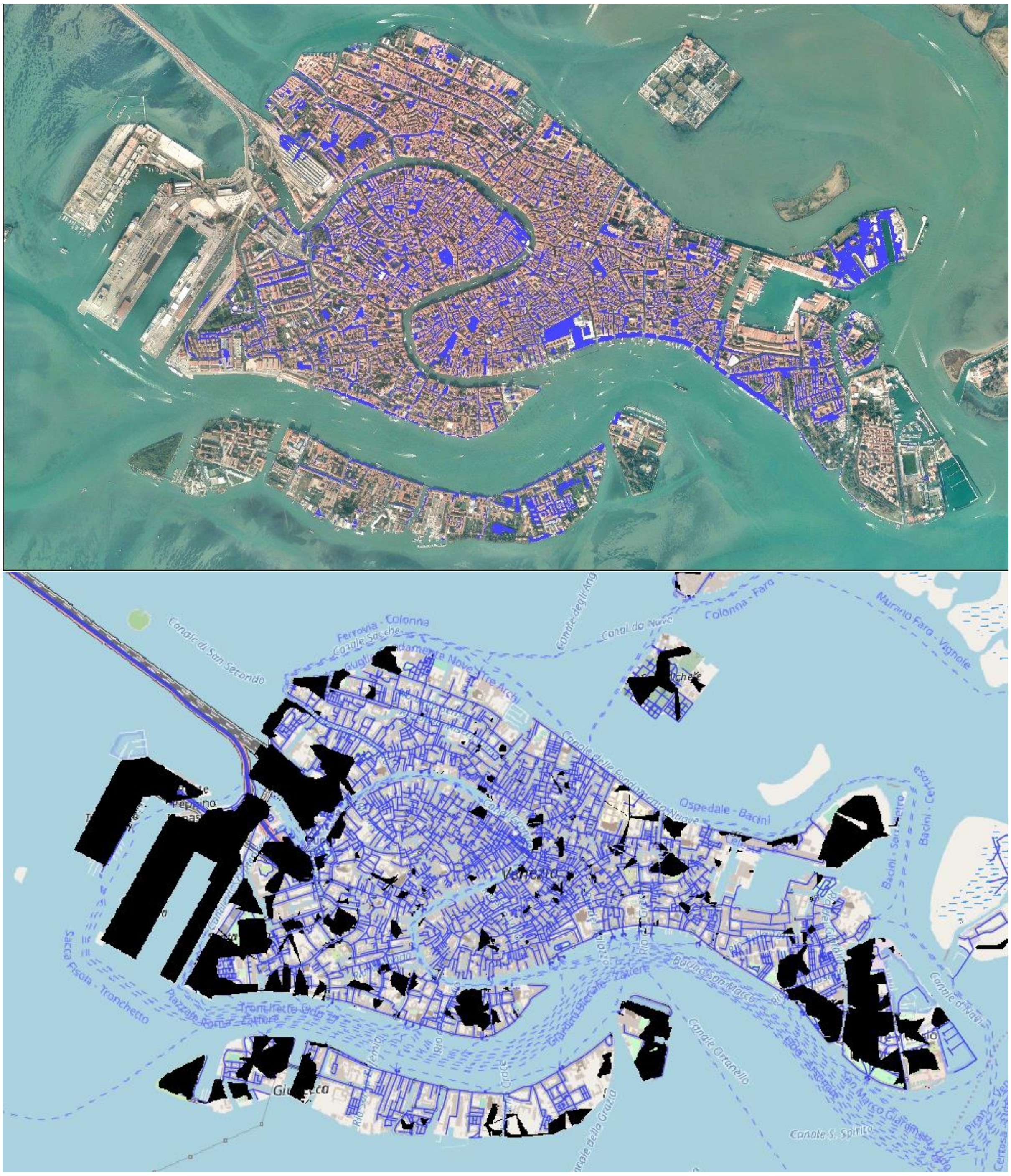


Figure 26 - Top figure: Flooded areas according to the MoSE website (Ministry of Infrastructure and Transport, 2020). Bottom figure: Flooded areas according to the model at 1.9m and a threshold of 0.3m. The black areas are dry and the blue roads represent the flooded roads

Figure 27 - Flooded areas according to the model at a water level of 0.9 m and a threshold of 0.3 m. The black areas are considered dry and the blue roads represent the flooded roads

St. Mark's square starts flooding at a water level of 0.8 m (BBC News, 2019). According to the model, including the threshold of 0.3 m, parts of the square start indeed flooding at a water level 0.8 m. The whole square is flooded at a water level of 1 m.

In a different flood assessment conducted in Florence, a threshold of 0.25 m is used (Arrighi, 2015). In the report, it is stated that the 0.25 m threshold represents the average elevation of the building's entrance door upon the road level, but the elevation of the entrance doors can be significantly higher for historical buildings. With this in mind, the chosen threshold of 0.3 m seems to be a reasonable assumption. Therefore, in all calculations and images made with the model in this report, the threshold of 0.3 m is used.

4.5 Flooded objects

As stated before, the water level during the 2019 flood event was 1.87 m. The model is run for this water level to gain insight into the number of flooded objects during this flood event. A table containing the total of all flooded polygons is shown below in Table 6. The information corresponding to all sub-areas is included.

Table 6 - Flooded buildings at water level of 1.87m

Sub area	Number of flooded buildings	Total area of flooded buildings	Mean water depth of flooded buildings
City center	5176	2559925 m^2	0.91 m
Lido	2287	581950 m^2	0.99 m
Pellestrina	697	138625 m^2	0.85 m
Other islands	2192	654700 m^2	1.04 m

Comparing these numbers to the total number of buildings in each sub-area determines the percentage of flooded buildings. The total amount of buildings is determined by counting the number of rows in the polygon attribute table created by the model. See Table 45 in Appendix C.

A table containing the total number of all flooded lines (or roads) is shown below in Table 7. The information corresponding to all sub-areas is included. Just as in the method applied to buildings, a line is considered flooded if it is overlapped by at least one flooded cell of 25 m^2. As explained previously, lines representing roads located on bridges were not considered to prevent error.

Table 7 - Flooded roads at water level of 1.87m

Sub area	Number of flooded roads	Total length of flooded roads	Mean water depth of flooded roads
City center	4114	151355 m	0.96 m
Lido	447	57610 m	1.06 m
Pellestrina	156	22415 m	0.88 m
Other islands	589	61375 m	1.16 m

Comparing these numbers to the total number of roads in each sub-area determines the percentage of flooded roads. The total number of roads is determined by counting the number of rows in the polygon attribute table created by the model. See Table 46. in Appendix C.

New matrices can be made containing only information about certain objects of interest by searching through the created matrices for certain keywords using the strcmp() function. The results of these searches can be found in Appendix D.

4.6 Cost of Damages

The estimated damages can now be expressed in euros. The total damage can be estimated by using the obtained information about the flooded objects (see Appendix D). A report compiled by Deltares enumerates the cost of flooded buildings and roads (Deltares, 2015). These provided costs are used to estimate the cost of damages in Venice. This report uses costs associated with Dutch buildings and Australian roads, which likely differ from the costs of Venetian buildings and roads. Therefore, these cost calculations are only considered estimations rather than correct amounts. Only the direct damages are considered, therefore excluding indirect damages such as business interruption and the impact on tourism.

The cost of damages to buildings as given by the Deltares report are either in cost of damage per building or per m^2. In the case of roads, the cost of damage is given in either cost per meter or cost per m^2. All required information about the buildings and roads is collected in section 4.5, except for the flooded roads in m^2. Average widths for each road type need to be assumed. This will be discussed later in this section.

First, the numbers pertaining to cost of damage according to the Deltares report are reviewed. For some objects, the damage costs are dependent on the water depth. In such cases, the maximum cost of damage to the object is given and subsequently a fraction of that maximum cost is taken. This fraction depends on the water depth and is chosen according to a damage curve. The damage numbers are converted to euros and adjusted for inflation. Finally, these numbers will be used together with the information about the flooded objects (see Appendix D) to calculate the damage to these flooded objects. The damage costs in the Deltares report are divided in roads, houses and businesses. The businesses are again subdivided according to the available information listed in Appendix D.

4.6.1 Damage numbers

In Table 8, the costs of damage of different types of roads are listed. These values concern Australian roads. Taking inflation into account, the damages from the year 2007 need to be multiplied by 1.21 to reach the value of the damages in 2020.

Table 8 - Infrastructure costs for different road types (in 2007 euros) (Deltares, 2015)

Road	Price [€/m]
Path	147
Secondary road	134
Road 3-6 m	495
Road over 6 m	870
Expressway	870

Cleaning of debris on streets due to flooding are as follows (M. Reese, 2003):

- Cleaning of sealed surfaces: approximately 6.00 euros per m^2 (2001 value)
- Cleaning of unsealed surfaces: approximately 3.60 euros per m^2 (2001 value)

It is assumed that most road surfaces in Venice are unsealed. These damages are from the year 2001 and due to inflation need to be multiplied by 1.37 to reach the value of the damages in 2020. The damages and cleaning costs of the roads are independent of the water depth.

In Table 9, the maximum costs of damage to several types of businesses are given. These values are taken from data pertaining to Dutch businesses. The damages are from the year 2015 and need to be multiplied by 1.06 to consider inflation.

Table 9 - The maximum physical damage to businesses (euros/m2) (in 2015 euros) (Deltares, 2015)

Category	Maximum damage [€/m^2]
Meeting facilities	168
Health services	1974
Industry	1497
Offices	1283
Education	993
Sports	102
Retail and commerce	1508

These values represent the maximum cost of damage that might occur, indicating that the actual costs of damage are most likely smaller. A certain percentage of the maximum cost of damage to the businesses is used depending on the water depth. For this a damage curve will be used. Figure 28 shows the damage curve for businesses. Since the type of businesses are rather vague and the graph does not show exact numbers, it is assumed that for a water depth of 1.87 m the factor is 0.5 for all business types.

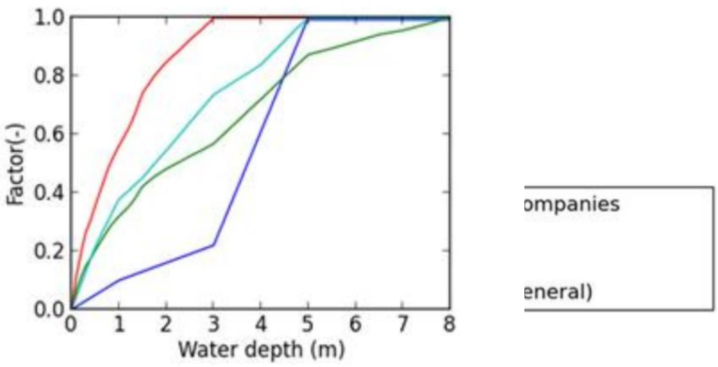


Figure 28 - Water depth compared to damage factor for businesses (Deltares, 2015)

In Table 10, the maximum damage to several types of houses are given. In the Deltares report, the maximum damage is calculated by taking the mean market value of the house, subtracting the value of the land (which is assumed to be 21 % of the market value) and add €70,000 to represent the household effects (Deltares, 2015). These values are found using data pertaining to Dutch houses. These costs are from the year 2000 and therefore need to be multiplied by 1.41 to account for inflation.

Table 10 - Maximum damage values per housing type (in 2000 euros) (Deltares, 2015)

Residence category	Price [€]	Value of land (21 % of the market value) [€]	Reconstruction value [€]	Maximum damage HIS-SSM [€]
Low-rise building	127.000	25.000	102.000	172.000
Middle-range building	127.000	25.000	102.000	172.000
High-rise building	127.000	25.000	102.000	172.000
Farms	427.000	95.000	332.000	402.000
Single-family house	219.000	48.000	171.000	241.000

A certain percentage of the maximum damage to the houses is used as the values are dependent on the water depth. These depth-dependent percentages form the damage curve and are listed in Table 11.

Table 11 - Water depth compared to percentage of the damage for buildings of 6 floors (Deltares, 2015)

Water depth [m]	Percentage of building volume under water	Percentage of the total damage according to HIS-SSM
0	0	0
1	7	20
2	13	38
3	20	52
4	26	63
5	33	73

The relevant building types for which damages can be calculated with the tables from the Deltares report are houses, industry, health services, education and sports facilities. For the churches, damages will be calculated according to the information obtained by the internet literature and news article research. All other buildings types, which are townhalls, theatres, police stations, fire stations, parking lots and greenhouses, will be considered industry.

4.6.2 Damages to houses

The number of flooded houses is estimated by subtracting all other specified types of flooded buildings from the total amount of flooded buildings. Although there is a keyword 'residential' in the polygon matrices, this will not be used since it is used for many non-residential buildings, therefore producing inaccurate results.

Table 12 - Calculation of flooded amount of houses

	City center	Lido	Pellestrina	Other islands
Number of flooded buildings	5176	2287	697	2192
Number of flooded industries	120	35	12	131
Number of flooded churches	107	5	4	17
Number of flooded townhalls	2	0	0	1
Number of flooded universities	15	0	0	1
Number of flooded schools	14	5	0	4
Number of flooded sports facilities	1	0	1	2
Number of flooded theatres	4	0	0	0
Number of flooded police stations	4	0	0	0
Number of flooded fire stations	0	0	0	0
Number of flooded hospitals	1	0	0	0
Number of flooded parking lots	1	0	0	0
Number of flooded greenhouses	1	0	0	62 -
Number of flooded houses	4906	2242	680	1974

It is assumed that the flooded buildings are low-rise buildings to middle-range buildings. This means that the maximum damage to a house is €172,000 (see Table 10). The average water depth will be used to determine the actual damage. Since the mean water level of flooded buildings is approximately 0.95 meter (see Table 6), the percentage of the total damage to houses is iterated at 19% (see Table 11). Taking inflation into account, the damage to a house is therefore €172,000 · 0.19 · 1.41 = €46,079. The total damage to houses is therefore reached by multiplying the number of flooded houses by €46,079.

Table 13 - Damage to houses at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Damage to houses	€ 226,323,068	€ 103,308,670	€ 31,333,584	€ 90,959,551

4.6.3 Damage to industry

As stated before, the total area of flooded industry, townhalls, police stations, fire stations, parking lots and greenhouses is added together and will be regarded as industry.

Table 14 - Calculation of area of flooded industry

	City center	Lido	Pellestrina	Other islands
Total area of flooded industry	160000 m^2	23075 m^2	10725 m^2	137150 m^2
Total area of flooded townhalls	3025 m^2	0 m^2	0 m^2	475 m^2
Total area of flooded theatres	2900 m^2	0 m^2	0 m^2	0 m^2
Total area of flooded police stations	5900 m^2	0 m^2	0 m^2	0 m^2
Total area of flooded fire stations	0 m^2	0 m^2	0 m^2	0 m^2
Total area of flooded parking lots	2425 m^2	0 m^2	0 m^2	0 m^2
Total area of flooded greenhouses	525 m^2	0 m^2	0 m^2	24100 m^2 +
Total area	174775 m^2	23075 m^2	10725 m^2	161725 m^2

The maximum damage to industry is according to Table 9 €1497 per m^2. Since this is the maximum damage, the real occurring damage is probably a lot smaller. It is assumed from the damage curve in Figure 28 that the occurring damage to flooded industry amounts the maximum damage multiplied with a factor 0.5. Taking inflation into account, the maximum damage to industry per m^2 becomes €1497 · 0.5 · 1.06 = €793.41. The total damage to industry is therefore reached by multiplying the area of flooded industry by €793.41.

Table 15 - Damage to industry at water level of 1.87m

	City center	Lido	Pellestrina	Other Islands
Damage to industry	€ 146,988,327	€ 19,406,412	€ 9,019,882	€ 136,013,086

4.6.4 Damage to health services

The total area of flooded Hospitals is regarded as health services.

Table 16 - Total area of flooded hospitals at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Total area of flooded hospitals	6500 m^2	0 m^2	0 m^2	0 m^2

The maximum damage to health services is according Table 9 €1974 per m2. Since this is the maximum damage, the real occurring damage is probably a lot smaller. It is assumed from the damage curve in Figure 28 that the occurring damage to flooded health services amounts the maximum damage multiplied with a factor 0.5. Taking inflation into account, the maximum damage to industry per m2 becomes €1974 · 0.5 · 1.06 = €1046.22. The total damage to health services is therefore reached by multiplying the area of flooded health services by €1046.22.

Table 17 - Damage to health services at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Damage to health services	€ 6,800,430	€ -	€ -	€ -

4.6.5 Damage to education

The total area of flooded university buildings and schools are added together and will be regarded as education.

Table 18 - Calculation of area of flooded education

	City center	Lido	Pellestrina	Other islands
Total area of flooded universities	19900 m^2	0 m^2	0 m^2	4450 m^2
Total area of flooded schools	38200 m^2	1050 m^2	0 m^2	4050 m^2 +
Total area education	58100 m^2	1050 m^2	0 m^2	8500 m^2

The maximum damage to education is according Table 9 €993 per m2. Since this is the maximum damage, the real occurring damage is probably a lot smaller. It is assumed from the damage curve in Figure 28 that the occurring damage to flooded education amounts the maximum damage multiplied with a factor 0.5. Taking inflation into account, the maximum damage to education per m2 becomes €993 · 0.5 · 1.06 = €526.29. The total damage to education is therefore reached by multiplying the area of flooded education by €526.29.

Table 19 - Damage to education at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Damage to education	€ 30,577,449	€ 552,605	€ -	€ 4,473,465.00

4.6.6 Damage to sports facilities

The total area of flooded sports facilities is as follows:

Table 20 - Total area of flooded sports facilities at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Total area of flooded sports facilities	2600 m^2	0 m^2	25 m^2	450 m^2

The maximum damage to sports facilities is €102 per m2 according to Table 9. Since this is the maximum damage, the real occurring damage is probably a lot smaller. It is assumed from the damage curve in Figure 28 that the occurring damage to flooded sports facilities amounts the maximum damage multiplied with a factor 0.5. Taking inflation into account, the maximum damage to sports facilities per m2 becomes €102 · 0.5 · 1.06 = €54.06. The total damage to sports facilities is therefore reached by multiplying the area of flooded sports facilities by €54.06.

Table 21 - Damage to sports facilities at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Damages to flooded sports facilities	€ 140,556	€ -	€ 1,352	€ 24,327

4.6.7 Damage to roads

All damages to the roads are independent of the water depth. The damage to motorways is according to Table 8 €870 per meter (expressway). Taking inflation into account, the damage to motorways per meter becomes €870 · 1.37 = €1191.90.

Table 22 - Total length of flooded motorways at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Total length of flooded motorways	1020 m	0 m	0 m	0 m

The damage to footpaths is according to Table 8 €147 per meter (paths). Taking inflation into account, the damage to footpaths per meter becomes €147 · 1.37 = €201.39.

Table 23 - Total length of flooded footpaths at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Total length of flooded footpaths	147975 m	17420 m	9220 m	37755 m

The damage to residential roads is according to Table 8, €134 per meter (secondary road). Taking inflation into account, the damage to residential roads per meter becomes €134 · 1.37 = €183.58.

Table 24 - Total length of flooded residential roads at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Total length of flooded residential roads	2345 m	29965 m	10305 m	8450 m

As mentioned earlier in this section, according to Reese et al. (M. Reese, 2003), the cleaning costs of roads due to flooding are €3.60 per m^2 assuming an unsealed surface. The costs of cleaning the roads after the flood can be calculated by multiplying the total surface of the flooded roads by €3.60. The total length is known. The widths of the motorways, footpaths and residential roads are assumed to be 6 m, 2 m and 4 m respectively.

The total damage to roads and the total cleaning costs of the roads are as follows.

Table 25 - Total damage and cleaning costs of roads at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Total damage to roads	€ 27,774,286	€ 7,957,021	€ 3,310,814	€ 8,085,565
Total cleaning costs roads	€ 1,536,071	€ 762,980	€ 294,243	€ 539,117

4.6.8 Damage to churches

At the very least €4.5 million is needed to tackle some of the problems that have emerged due to the flooding of 85 churches (The Art Newspaper, 2020). This means that at least €4,500,000 / 85 = €52,941 is needed per church. However, to restore the church instead of 'tackling some of the problems', it can be said that double that amount is actually needed. This means the damage is €52,941 · 2 = €106,000 per church. This is probably still a very modest estimation, since €5.5 million damage was done to the St. Mark's

Basilica only (Travel and Leisure, 2019). The total amount of flooded churches is shown below.

Table 26 - Total amount of flooded churches at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Amount of flooded churches	107	5	4	17

The total cost of damage to churches therefore is as follows.

Table 27 - Total damage to churches at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Damage to churches	€ 11,342,000	€ 530,000	€ 424,000	€ 1,802,000

4.6.9 Total Damages

When all these damages are added together, the total direct damage due to the November 2019 flood is estimated. Again, these direct damages exclude indirect damages like business interruption and the impact on tourism.

Table 28 - Total direct damage at water level of 1.87m

	City center	Lido	Pellestrina	Other islands	Total
Total direct damage	€ 451,221,711	€ 132,517,687	€ 44,383,874	€ 241,897,111	€ 870,020,384

As touched upon earlier in this report, the damage to public property was estimated to be €360 million just after the flooding and the mayor of Venice stated that the damages might reach €1 billion (DW, 2019). The stated €1 billion probably relates to the city center only an includes indirect damages as well. The calculated €451 million of direct damages to the city center and €870 million of total direct damages are therefore quite a reasonable estimate. Overall it can be stated that these numbers are quite representative, when compared with the numbers from the online literature and news article research.

4.7 Cultural heritage

As mentioned in the introduction of this report, there are a lot of historic buildings and structures throughout Venice and the whole lagoon. Many of the buildings and structures are regarded as historically important and are therefore listed as cultural heritage. This means that these buildings and structures need to be protected and conserved. Because of the threatening water in Venice, this is an especially important issue. UNESCO plays a large role in the protection of cultural heritage.

On the UNESCO website (UNESCO, 2020), the following is stated about the flood threat: 'The phenomenon of high water is a threat to the integrity of cultural, environmental and landscape values of the property. The occurrence of exceptional high waters poses a significant threat to the protection and integrity of Venice lagoon and historic settlements. The increase in the frequency and levels of high tides, in addition to the phenomenon of wave motion caused by motorboats, is one of the main causes of deterioration and damage to the building structures and urban areas.'

4.7.1 Amount of flooded cultural heritage

The same model as has been elaborated earlier, will be used to assess the amount of flooded cultural heritage during the November 2019 flood event (water level of 1.87 m above Punta della Salute). For this, distinct data will be used which contains solely polygons of cultural heritage (Commune di Venezia, 2019), instead of the polygons from Open Street Maps. These polygons do not contain useful information about the cultural heritage they represent. Therefore, overlaying and clipping with the OSM polygons is done. In this way, the OSM polygons that are cultural heritage will remain and all other polygons will be deleted. With the remaining polygons, just as earlier, the water depth raster will be used to analyze which polygons are flooded and information about the flooded polygons is added to a matrix.

Figure 29 shows the polygons of the cultural heritage (red) overlaying the polygons from Open Street Maps (green). The cultural heritage polygons do not completely overlap the OSM polygons but are a bit off. This might be due to the cultural heritage polygons originally not being in the EPSG:3003 projection.

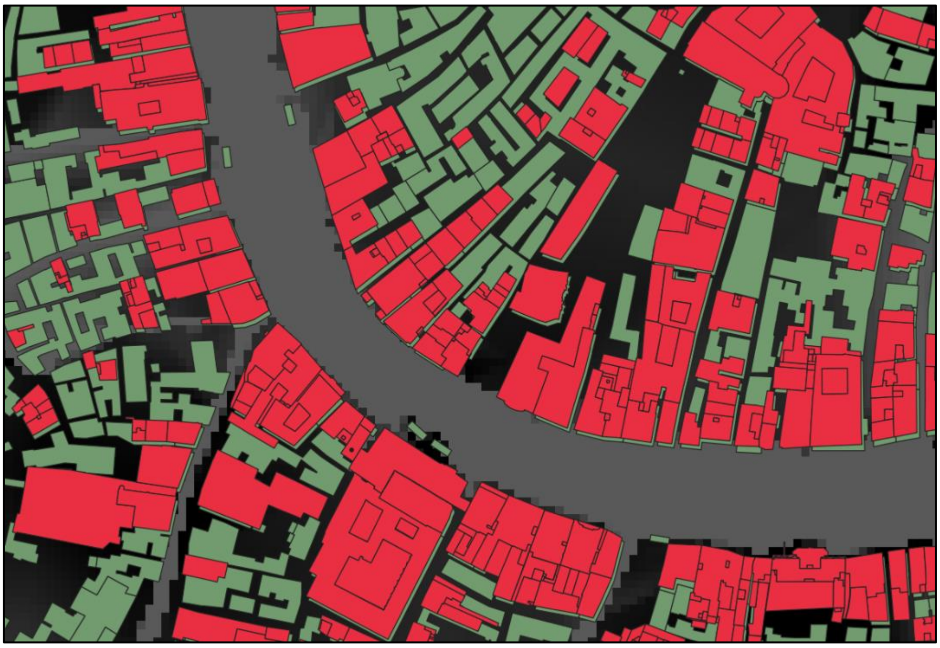


Figure 29 - Polygons of cultural heritage (red) overlaying the polygons from Open Street Maps (green) and the water depth raster

Since the polygons are not completely overlapping, some polygons might get duplicated when clipping is done. It is important that these duplicated layers are deleted when analyzed in MATLAB.

InTable 29, the total amount of buildings being cultural heritage are shown per sub-area.

Table 29 - Total amount of flooded cultural heritage at water level of 1.87m

Sub area	Amount of flooded buildings	Total area of flooded buildings	Mean water depth of flooded buildings
City center	2090	990875 m^2	0.89 m
Lido	124	63950 m^2	0.66 m
Pellestrina	6	2300 m^2	1.08 m
Other islands	201	64375 m^2	1.03 m

When comparing these numbers to the total amount of buildings per sub area, the percentage of flooded cultural heritage can be determined. See Table 47 - Percentage of flooded cultural heritage at water level of 1.87m in Appendix C.

To get some insight in the flooded cultural heritage per type of buildings that get flooded, tables are added per building type in Appendix E.

4.7.2 Damages to cultural heritage

By using the same method as in Section 4.6, the damages to cultural heritage are calculated. For this, the flooded cultural heritage is used, as can be found in Appendix E. The resulting damages to cultural heritage for each building type are added in Appendix F. When all these damages are added together, the total direct damage to cultural heritage due to the November 2019 flood is estimated. See Table 30.

Since the damages to regular buildings from Section 4.6 have been used, it must be noted that the estimation of the damages might be rather inaccurate. This has to do with the fact that damages to cultural heritage might be different because of possible specialized restauration work that has to be carried out.

Table 30 - Total direct damage to cultural heritage at water level of 1.87m

	City center	Lido	Pellestrina	Other islands	Total
Total direct damage cultural heritage	€ 210,901,906	€ 14,210,650	€ 336,394	€ 18,655,003	€ 244,103,954

It can be concluded that during the November 2019 flood event, the damage to cultural heritage was approximately 28% of the total damage.

4.8 Flooded area

In this section, the bathtub model approach as elaborated in Section 4.3 will be used to determine the flooded area as a function of the water level. First, an explanation is given of how the calculation of the flooded area at a certain water level is made. Then, some statistics are done for an array of water levels.

4.8.1 Approach

The areas over which the flooded percentage is calculated, are the same sub areas as defined in Figure 19. The percentages of flooded area for each sub area is calculated as follows.

The raster with surface elevation values as described in Section 4.3 is loaded into MATLAB as a matrix. Then, two water levels are defined: the first being the regular water level (0 meter above Punta della Salute), the second being the water level at which the percentage of flooded area is wished. A loop is made that records in a new matrix in what cells of the raster the surface level elevation is equal to or larger than the water level minus a certain threshold. Again, as earlier, this threshold is defined at 0.3 m. The cells in this new matrix will contain a 0 if the surface level elevation is smaller than the water level minus the threshold and will contain a 1 if the surface level elevation is larger than the water level minus the threshold. The loop creates such a matrix for both water levels. The number of occurrences of “1” in each matrix is counted and the following calculation is made.

$$Percentage = 100\% - (\frac{OnesHWL}{OnesMWL} \cdot 100\%)$$

In which:

Percentage = The percentage of the area that is flooded.

OnesHWL = The number of occurrences of “1”in the matrix for the water level at which the percentage of the flooded area is desired, representing the number of dry cells at the high water level.

OnesMWL = The number of occurrences of “1” in the matrix for the regular water level (0 m above Punta della Salute), representing the number of dry cells at mean water level.

With this formula a comparison is made between the numbers of dry cells of both water levels. The dry area at high water level is compared to the dry area at mean water level. Making this comparison with the flooded cells would not work, because the island is only a small fraction of the considered sub areas. Since at mean water level none of the sub areas are completely flooded, dividing by zero will not occur.

For the flood event of November 2019, the percentages of flooded area are shown per sub area in Table 31. Since the bathtub model probably overestimates the flooded area a bit (see section 4.3), these percentages are most likely a bit overestimated as well.

Table 31 - Percentage of flooded areas at water level of 1.87m

	City center	Lido	Pellestrina	Other islands
Percentage	87.9 %	79.0 %	74.1 %	86.3 %

It is possible to use the created matrices to make plots of the dry and flooded areas. In Figure 30 on the next page, on the left, the sub areas are shown for mean water level (0 % flooded) and on the right, the sub areas are shown for a water level of 1.87 m (flooded percentage as shown in Table 31).

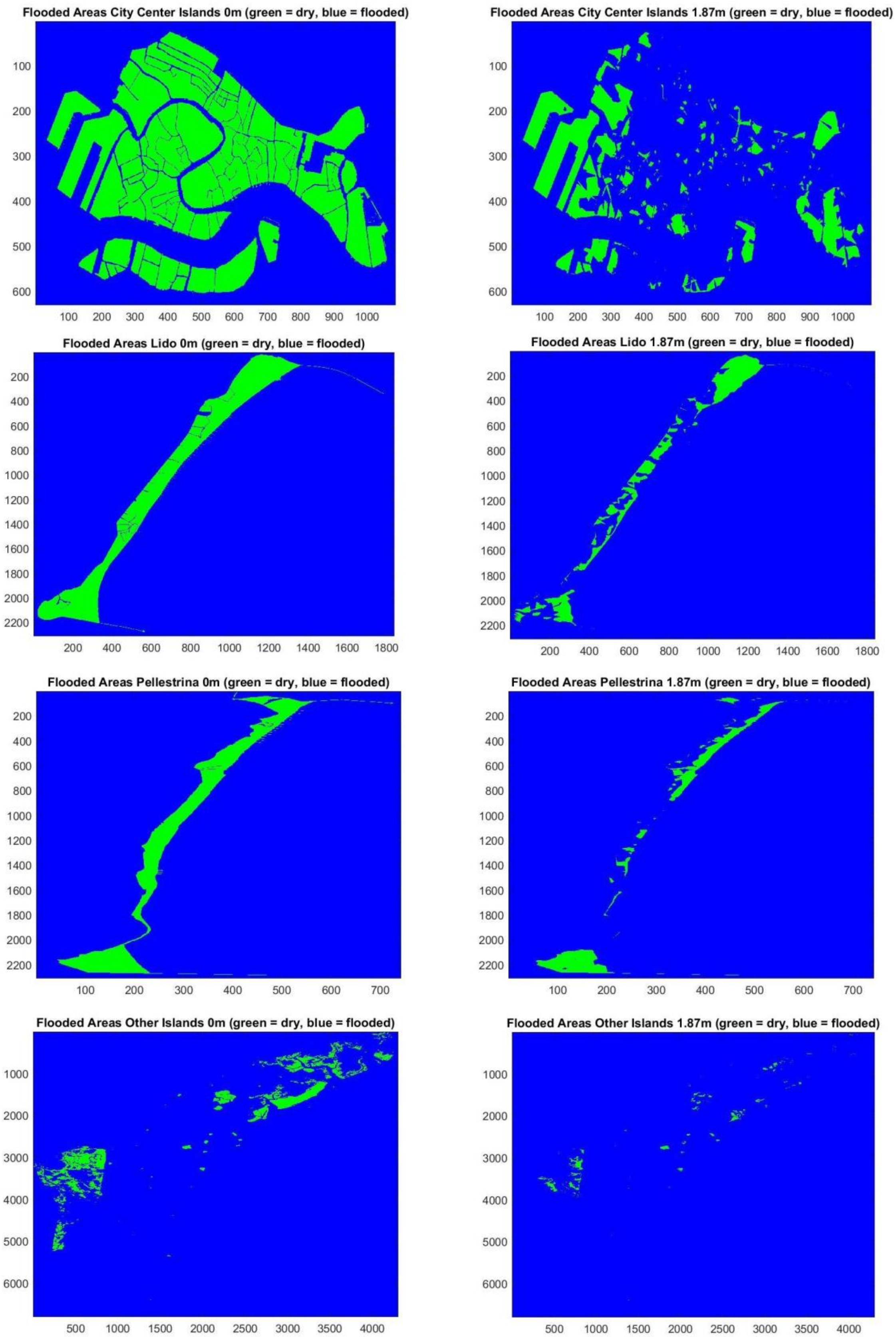


Figure 30 - From top to bottom on the left: Dry areas at water level of 0m (0 % flooded) for respectively the city center, Lido, Pellestrina and the other islands. From top to bottom on the right: Dry areas at water level of 1.87m for respectively the city center, Lido, Pellestrina and the other islands

To clarify which areas are flooded at a water level of 1.87 m, figures can be found in Appendix G.

4.8.2 *Statistics flooded area*

When the calculation for the percentage of flooded area is made for a large amount of water levels, statistics can be used to gain information about what impact any water level has on Venice. This is done for all sub-areas.

The percentage of flooded area is calculated for water levels between 0 and 2 m with an interval of 0.01 m. A cumulative distribution function (CDF) is made for each sub area. See Figure 31. From these graphs it is possible to easily read the percentage of the area that is flooded at any water level. Again, these percentages are probably slightly overestimated, because of the overestimated flooded area. Please keep in mind that a water level of 0 m in these plots represents mean water level (0 m above Punta della Salute).

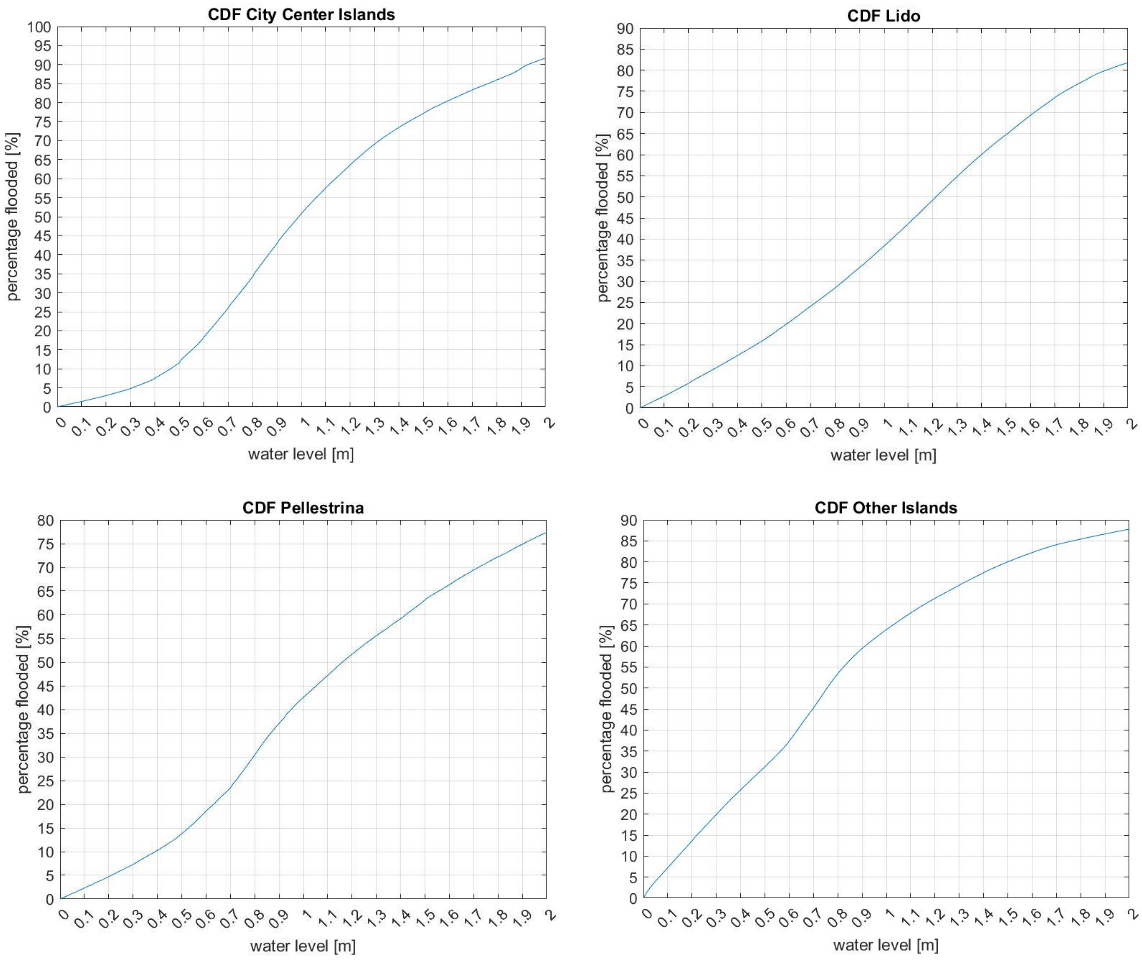


Figure 31 - Cumulative distribution functions of the flooded area over the water level for respectively the city center, Lido, Pellestrina and the other islands

Also, by taking the derivative of the cumulative distribution function, a probability density function (PDF) is made for each sub area. These can be found in Appendix H.

4.9 Closed Mo.S.E. barrier

According to Section 3.5, in the case of a high water event, the Mo.S.E. barrier begins closing before a water level of 1.1 m above Punta della Salute is reached. Although the barriers start closing at a varying water level according to the severity of the imminent high water event, the design water level when closed is 1.1 m at maximum. Therefore, if the Mo.S.E. barrier would have been operational during the November 2019 flood event, the maximum possible water level would have been 1.1 m.

The impact and damage due to a water level of 1.1 m is assessed here, which represents the state of Venice during a severe storm during which the Mo.S.E. barrier is operational.

According to Mo.S.E. website still 12% of Venice is flooded at a water level of 1.1 meter. This finding is compared to the resulting plot seen in Figure 32 (Piano Generale degli Interventi, 2020).

Figure 32 - Flooded areas according to the Mo.S.E. website at water level of 1.1m (CVN, 2020)

In Figure 33, the dry areas are shown in black just as in Section 4.4.

Figure 33 - Dry and flooded areas according to the model at water level of 1.1m

By doing the same calculation as in Section 4.8, the percentage of the areas that are flooded at a water level of 1.1 m are shown in Table 32.

Table 32 - Percentage of the flooded area at water level of 1.1 m

	City center	Lido	Pellestrina	Other islands
Percentage	57.6 %	43.7 %	47.2 %	67.8 %

The same analysis as elaborated in Section 4.3 is done for a water level of 1.1 m. The resulting amount of flooded buildings and roads can be seen in Table 33 and Table 34. More detailed information about the flooded buildings per building type is added in Appendix I.

Table 33 - Total amount of flooded buildings at water level of 1.1 m

Sub area	Amount of flooded buildings	Total area of flooded buildings	Mean water depth of flooded buildings
City center	1314	519850 m^2	0.63 m
Lido	893	245400 m^2	0.69 m
Pellestrina	126	22325 m^2	0.60 m
Other islands	897	233150 m^2	0.72 m

When comparing these numbers to the total amount of buildings per sub area, the percentage of flooded buildings can be determined. See Table 48 in Appendix C.

Table 34 - Total amount of flooded roads at water level of 1.1m

Sub area	Amount of flooded roads	Total area of flooded roads	Mean water depth of flooded roads
City center	1244	42165 m^2	0.74 m
Lido	197	19035 m^2	0.80 m
Pellestrina	47	5800 m^2	0.67 m
Other islands	319	30845 m^2	0.78 m

When comparing these numbers to the total amount of roads per sub area, the percentage of flooded roads can be determined. See Table 49 in Appendix C.

The total amount of flooded cultural heritage when the barrier is closed, is shown in Table 35.

Table 35 - Total amount of flooded cultural heritage at water level of 1.1m

Sub area	Amount of flooded buildings	Total area of flooded buildings	Mean water depth of flooded buildings
City center	448	183550 m^2	0.59 m
Lido	19	4450 m^2	0.25 m
Pellestrina	3	850 m^2	0.58 m
Other islands	81	25700 m^2	0.70 m

4.9.1 Damages with closed Mo.S.E. barrier

By using the exact same method as in Section 4.6, the damages when the Mo.S.E. barrier is closed are calculated. For this, the flooded buildings and roads as can be found in Appendix I are used. The resulting damages with the closed Mo.S.E. barrier can be found in Appendix J for each building type.

When all these damages are added together, the total direct damage due to the November 2019 flood is be estimated for when the Mo.S.E. barrier is closed.

Table 36 - Total direct damage at water level of 1.1 m

	City center	Lido	Pellestrina	Other	Total
Total direct damage closed barrier	€ 113,872,675	€ 59,927,369	€ 11,589,639	€ 71,805,465	€ 257,195,149

It can be concluded that the damages are a lot smaller when the Mo.S.E. barrier is closed compared to when it is open (approximately €613 million less). The damages of €257 million are however still considerable.
Table 37 compares the flooded area, flooded buildings and roads and the damages of the November 2019 flood event with and without an operational Mo.S.E. barrier.

Table 37 - Comparison of impact with and without Mo.S.E. barrier

		November 2019 flood event (1.87 m)	November 2019 flood event with functioning Mo.S.E. barrier (1.1 m)	Reduction
City center islands	Flooded area	87.9%	57.6%	30.3%
	Flooded buildings	5,176	1,314	3,862
	Flooded roads	4,114	1,244	2,870
	Flooded cultural heritage	2,090	448	1,642
	Damage	€ 451,221,711	€ 113,872,675	€ 337,349,036
Lido	Flooded area	79.0%	43.7%	35.3%
	Flooded buildings	2,287	893	1,394
	Flooded roads	447	197	250
	Flooded cultural heritage	124	19	105
	Damage	€ 132,517,687	€ 59,927,369	€ 72,590,318
Pellestrina	Flooded area	74.1%	47.2%	26.9%
	Flooded buildings	697	126	571
	Flooded roads	156	47	109
	Flooded cultural heritage	6	3	3
	Damage	€ 44,383,874	€ 11,589,639	€ 32,794,235
Other islands	Flooded area	86.3%	67.8%	18.5%
	Flooded buildings	2,192	897	1,295
	Flooded roads	589	319	270
	Flooded cultural heritage	201	81	120
	Damage	€ 241,897,111	€ 71,805,465	€ 170,091,646
Total	Flooded area	81.8%	54.1%	27.8%
	Flooded buildings	10,352	3,230	7,122
	Flooded roads	5,306	1,807	3,499
	Flooded cultural heritage	2,421	551	1,870
	Damage	€ 870,020,384	€ 257,195,149	€ 612,825,235

Chapter 5:
The Mo.S.E. Project and its Delay

Luisa Caporalini

5.1 Introduction

Following the disastrous flooding event of 1966, the Ministry of Culture and Environmental Heritage planned a series of studies and research projects to find the best way to deal with the problem. These projects were designed to address the rise in sea levels as well as the frequency and intensities of high waters in Venice (Mazzolin & Micheletti, 2015). Following hydrodynamics studies, preliminary projects and evaluations described in the General Plan of Interventions (GPI) proposed in 1986 by the Consorzio Venezia Nuova (CVN, Lit. New Venice Consortium), the mega-project Riequilibrio e Ambiente (REA, *Lit. Rebalance and Environment*) came to life two years after (Seminara, 2008). The Mo.S.E. barrier is one part of the project. This section describes the design and the operational criteria of the Mo.S.E. barrier, contextualizing it within the legislative parameters of Venice Lagoon as well as the mega-project to which it belongs.

The following research questions, which are accompanied by 2 – 3 sub-questions each, will be explored and answered in the next chapter.

RQ1 What is the Mo.S.E. project and in what context can it be identified?
RQ1.1 What is the structure and the object of the mega-project set for the defense of Venice lagoon?
RQ1.2 What are the Mo.S.E. barrier mechanism and design criteria?
RQ1.3 Once completed, how and when will the Mo.S.E. barrier work?

RQ2 Which typical Large Infrastructure projects aspect most affected the Mo.S.E. project's process?
RQ2.1 Who oversees the Mo.S.E. project and how is it handled?
RQ2.2 What are the complexity variables that can be associated to the Mo.S.E. project?
RQ2.3 What were the most severe delays suffered and which were the causes behind them?

RQ3 Should the barrier have been operated during the emergency flooding event of 2019?
RQ3.1 What were the circumstances of the 2019 Venice flood event in terms of project completion?
RQ3.2 In relation to the flood event of 2019, what were the reasons behind the decision of not operating the barrier?

The sub-questions are answered throughout the paper and provide context for the answers of the main research questions which are discussed in the conclusion. Most of the literature used was found within the CVN Mo.S.E. project website and the related journals that the CVN published annually. More information was collected through a review of many publications available in main search online systems such as scholar.google.com and researchgate.com. Legislative articles and Public acts were also consulted in addition to the literature. A TOE – Technical, Organizational and External complexity framework is used to assess the project complexity and to define which is the most influenced project management area, that creates the extreme delay on the completion of the project, along with its overwhelming costs overruns. Furthermore, it was given us the opportunity to interview Dr. Ir. Giovanni Cecconi (former CVN representative) and Dr. Ir. Peter Westentorp (operation director at Strukton company). Both interviews provided precious information vital to the development of the present research, nevertheless are not official representatives from the CVN or other actors involved on the design, construction and operation of the Mo.S.E. barrier. Finally, it is worthy to mention that it was attempted to contact some of these representative, but due to the tight schedule and current conditions it was no possible to arrange any other interview.

5.2 The Mega-Project REA

The REA project envisages a complex system of interventions for the protection of the Venice Lagoon and adjacent urban areas. Among the planned operations, mobile works can be found at the port mouths to regulate the lagoon tide (Filippi, et al., 2016). This section and the corresponding subsections address the structure of the mega-project for the defense of the Venice Lagoon, answering question RQ1.1, which goes as follows:

RQ1.1 What is the structure and the object of the mega-project set for the defense of Venice lagoon?

5.2.1 Mega-Project History

The 1966 flooding event necessitated the implementation of a special defense system. To address the problem, the Special Law (171/73) was written in 1973. Law 171/73 categorized the safeguarding of both the City of Venice and the Venice Lagoon as a matter of national interest (Commissione VIA, 1998). The law did not address the sea level rise issue specifically, instead delegating the inlet management entities to search for and apply the most efficient solution (Seminara, 2008). To comply with the aforesaid law, a committee of magistrates and local governmental entities called "Comitatone" was established and appointed to monitor of the activities.

In 1975, the Ministry of Public Works (MPW) called an international competition for the design and construction of a high tide defenses system. Five groups of companies took part in the competition. However, no presented solution completely satisfied the requirements set by the primary Special Law (Mazzolin & Micheletti, 2015). The projects were not accepted mainly for two reasons. Firstly, the designers considered the safeguard of the environmental and economic heritage of the area secondary to the reduction of the sea levels, which were not significant enough for the scope of the project. Secondly, the projects didn't address the problem related to the vivification of the north-east lagoon, considered important by the commissioner (Seminara, 2008).

In 1984 a New Special Law (798/84) for the protection of Venice Lagoon was written and approved, which established a committee of magistrates and local government entities called "Comitatone"[5] to monitor the activities. This law created the position Magistrate of

[5] COMITATONE, composed by: Ministries of Infrastructure and Transport, Environment and Territorial Protection, Cultural Heritage and Activities, University Education and Scientific Research, the Chairman of the Water Authority, the Chairman of the Veneto Regional Authority, the mayors of Venice and Chioggia and

the Waters (MoW), which is similar in concept to the former Dutch Sijkswaterstaat, and the Ministry of Infrastructure and Transport (MIT), whose roles were to oversee the protection of Venice.

Eventually, in 1984, a cutting-edge design for the works for the protection of Venice Lagoon were commissioned to the Consortium Venezia Nuova (CVN) in accordance with the Law 798/84, on the basis of conventions held periodically with the Magistrate of the Waters and with regard to the directives stated in the GPI drafted by the Comitatone. The works for the Mo.S.E. project started in 2003. A visual timeline with the main milestones of the history of the project is described in Figure 34.

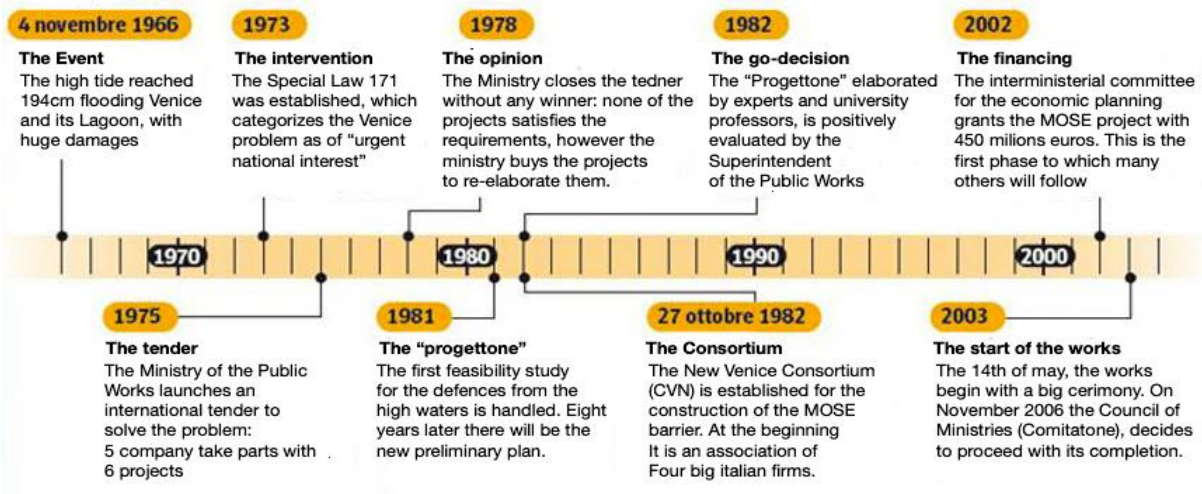


Figure 34 - Timeline of the approval procedure behind the MOSE project Specificata fonte non valida.

5.2.2 REA mega-project structure

The REA mega-project is considered an "open project," as the idea continuously evolves to consider a growing range of objectives. Each objective contributes to the physical and environmental safeguard of the entire lagoon system through many gradual, flexible and reversible interventions. Therefore, the MoW and CVN meet periodically to monitor the continuing evolution of the project.

The final total cost of the project was never determined since the project evolves so frequently. The government provides the finances based on the presentation of new interventions and objectives specified by the contractor. The need for financing is established in each convention between the contractor and the officers of the project.

5.2.3 REA mega-project problem statement and purpose

In the official Mo.S.E. project website, the CVN describes the problem statement through a description leading to the three main goals of the REA, which will be analyzed in respect to Kush's definition (see Tables 41, 42 and 43). The description goes as follows:

Treporti-Cavallino Local Authority and two representatives of the other local authorities along the lagoon boundary

"In recent centuries, a series of natural phenomena and factors due to human interventions have altered the lagoon environment. Over time, subsidence and eustatism have profoundly changed the relationship between land and water and caused a drop in soil of about 25 centimeters only in the last hundred years. [...] The interventions for the diversion of the rivers from the lagoon (from the 14th to the 19th century), to counter the landfill problem, have almost completely eliminated the supply of sand and sediment from the hinterland. Between the 19th and 20th centuries, the construction of the breakwaters at the port mouths, to ensure the transit of modern ships, also reduced the supply of sand from the sea. Furthermore, in the last century, the creation of the Porto Marghera petrochemical center has produced a very serious pollution of the waters and the seabed, while the excavation of deep navigation channels has led to significant changes in the lagoon hydrodynamics. At the end of the 1900s, the lagoon system had to face a multiplicity of problems, with ancient origins or with recent causes:

1. The rise in sea water levels, so Venice, Chioggia and other urban lagoon areas are increasingly flooded in the autumn and winter months;
2. The erosion of the coasts with the gradual disappearance of the beaches, essential to protect coastal towns from storm surges;
3. The degradation of the environment due to the deterioration of the quality of water and sediments and the loss of ecosystem habitats, such as sandbanks and slums."

Table 38 - Problem statement 1 analysis

What **is the problem?**	Increased number of flooding events
Who **is experiencing the problem?**	The lagoon system
Where **is the problem occurring?**	Urban lagoon areas
Why **does the problem occur?**	Rise in sea water levels
When **does the problem occur?**	Autumn and winter months

Table 39 - Problem statement 2 analysis

What **is the problem?**	Gradual disappearance of the beaches
Who **is experiencing the problem?**	The lagoon system
Where **is the problem occurring?**	On the coasts
Why **does the problem occur?**	Erosion of the coast
When **does the problem occur?**	Gradually through time

Table 40 - Problem statement 3 analysis

What is the problem?	Degradation of the environment, loss of ecosystem habitats
Who is experiencing the problem?	The lagoon system
Where is the problem occurring?	In the lagoon
Why does the problem occur?	Deterioration the quality of water
When does the problem occur?	Gradually through time

5.2.4 REA mega-project objectives

The objectives of the REA project are established by Law 798/84, which gives the local authorities the motivation and means to act on the protection of the lagoon and its architectural, urban and environmental recovery. These are summarized as follows (Special Law 798/84, Art.3a):

A. The hydrologic and morphologic rebalance of the lagoon,

B. The arrest and the reversal of the degradation process to which the lagoon is subject and the elimination of the relative causes that provoked it

C. The mitigation of the tide levels in the lagoon

D. The defense of urban centers through local protection and prevention systems,

E. The defense of urban centers through the implementation of mobile barriers at the lagoon inlets.

5.2.5 The mega-project scopes

In the Mo.S.E. project official website, the CVN divides the activities described in the GPI into three main scopes, upon a subject-of-intervention criteria:

1. Environmental defense
2. Storm surge defense
3. High tide defense

Relating to these objectives, the environmental defense scope (1) targets the objective A and B through the purification of disused landfills, the purification of polluting sites along with the protection and the reconstruction of lagoon habitats. Lastly, the high tide defense scope (2) targets objectives D and E through local defenses and the construction of the Mo.S.E. barrier. The storm surge defense scope (2) aims to satisfy objective C through the reinforcement of the shores. Figure 56, located in Appendix K, maps the various interventions specified in the GPI located in the lagoon as well as their completion status as of 2019.

5.3 The Mo.S.E. barrier design and mechanism

The most important part of the REA mega-project is the Mo.S.E. barrier. To ensure the complete defense of the Venice lagoon from high tides, a complex and integrated systems of works was conceptualized. This system includes four mobile barriers (see Figure 36), at the three lagoon inlets (Lido, Malamocco and Chioggia) for a total length of 1.6 km (Paolucci G. M., 2012). The gate arrays that make up the Mo.S.E will lie underwater out of sight when unused.

This section provides a geographical contextualization of the barriers in the lagoon, followed by a brief explanation of the project history and the choice of the design. Afterwards, a description of the barrier mechanism will be given and each of the main elements that make up the barrier are described. Lastly, production and assembly will be discussed, introducing the vehicles specifically built for the installation and maintenance of the barrier. This entire chapter addresses RQ1.2, which is repeated here:

RQ1.2 What are the Mo.S.E. barrier mechanism and design criteria?

Figure 35 - View of the Mo.S.E. barrier (Pietrobelli, 2020)

5.3.1 The Location

As suggested by the *Progettone*, the Mo.S.E. project is located at the mouths of the port of Lido, Malamocco and Chioggia. It consists of a series of barriers made up of mobile gates located at the lagoon mouths. The four defenses barriers are built as follows:

- 2 barriers at the Lido lagoon mouth, the two barriers are connected to each other by an intermediate island,
- 1 barrier consisting of 19 gates at the mouth of the port of Malamocco,
- 1 barrier of 18 gates at the mouth of the port of Chioggia.

The depths and pre-existing cross-sections of the mouth canals were not altered by the work. At the mouths of Lido and Chioggia, ports of refuge and small navigation basins allow the transit of boats for leisure, emergency vehicles and fishing boats even when the gates in operation. At Malamocco, a navigation lock was built to guarantee the transit of ships and operation of the port even when the gates are raised. The navigation lock is located on the south bank and is about 370 m long and 48 m wide. The lock is protected by an external wall that shelters the area from waves (CVN, 2014) (Deheyn & Shaffer, 2007).

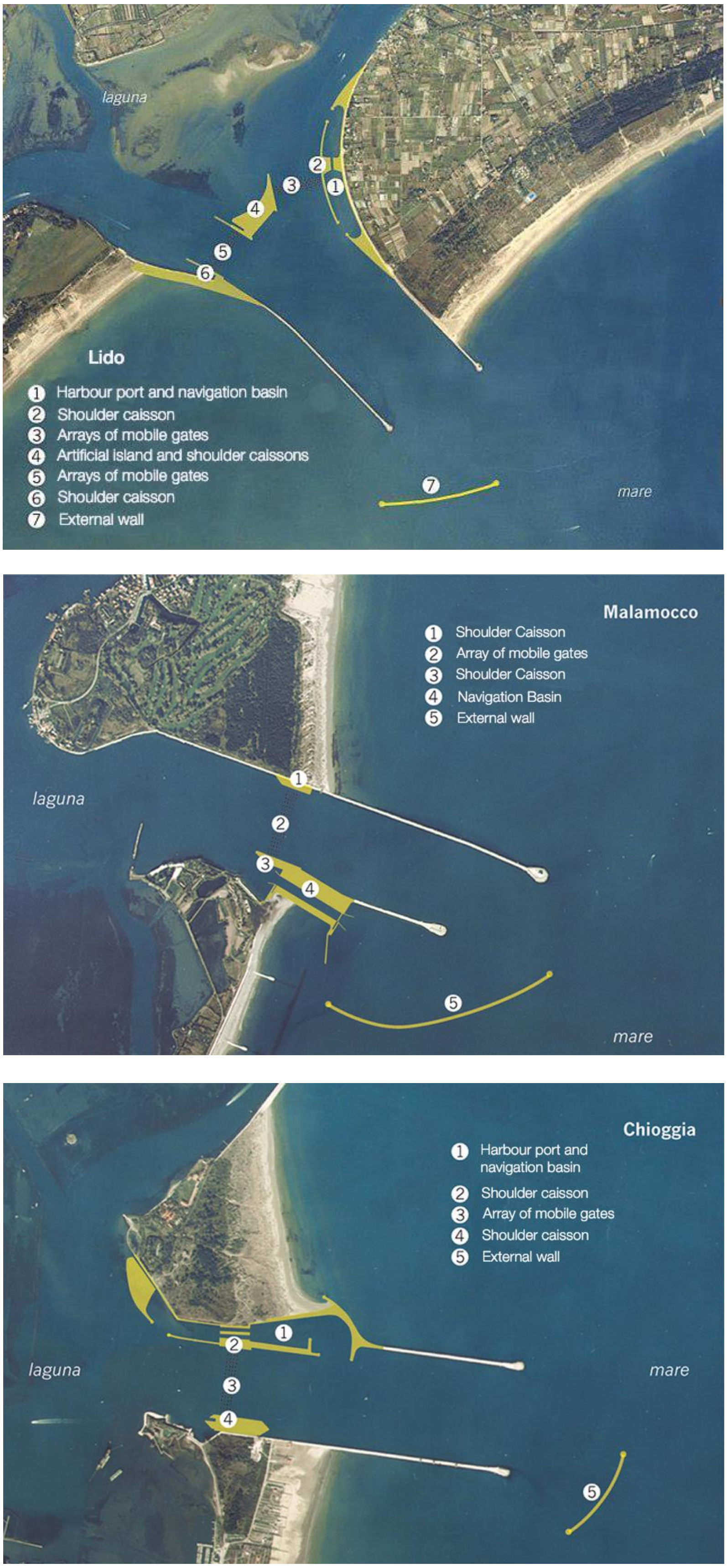


Figure 36 - From top to bottom: configuration of Lido, Malamocco and Chioggia inlets

5.3.2 *The Progettone and the history of the Mo.S.E. project*

Before the Mo.S.E. system criteria are analyzed any further, a premise regarding the rough draft of this complex project has to be pointed out. In 1980, the MoW and the MIT organized a committee of professors called Sette Saggi[6] (*Lit. Seven wise men*). The goal was to draft the high tide defense system which would be inserted into the landscape of the Venetian coasts at each lagoon mouth. The preliminary project was called the "Progettone" (*Lit. Big Project*) and was delivered one year later, in 1981. The conclusions of the Progettone, discussed in this paragraph, form the basis upon which the Mo.S.E. barrier was designed and implemented.

In the conclusions of the *Progettone*, the committee found the three lagoon inlets (Lido, Malamocco and Chioggia) to be the only locations where an attenuation of the almost periodical tidal waves could have been obtained in the lagoon. The most convenient solution for the protection of the Venice Lagoon is then investigated and presented with respect to the New Special Law 798/84.

The *Progettone* considered many different solutions to face the problem of the rising waters (Ghetti, et al., 1981). Considering the scope and the requirements set by the Special Law 798/84, many alternatives were eliminated for reasons discussed further on. The requirements set by this law can be summarized as (Scotti, 1994):

(A) The defense system should not foresee any reduction in the section of the mouth canals where they will be located. Any reduction would indeed result in a decrease of the natural water exchange flow, hence worsening the water quality levels and the sediments of the lagoon

(B) The defense system should not foresee intermediate nor emerging structures that would interfere with the ship traffic.

(C) The visual impact on the landscape should be reduced to the minimum possible, ensuring that, when the barrier is not in operation, the structures would be barely visible, if not entirely submerged.

(D) It is necessary to ensure the ship transit through the lagoon mouths, even during the barrier closure times, of fishing ships, emergency boats and similar activities.

[6] SETTE SAGGI COMMETTEE Composed by the experts: Augusto Ghetti, Enrico Marchi, Piero Matildi, Roberto Passino, Gianantonio Pezzoli, Roberto Frassetto and Jan F. Angema (Professor from TU Deflt)

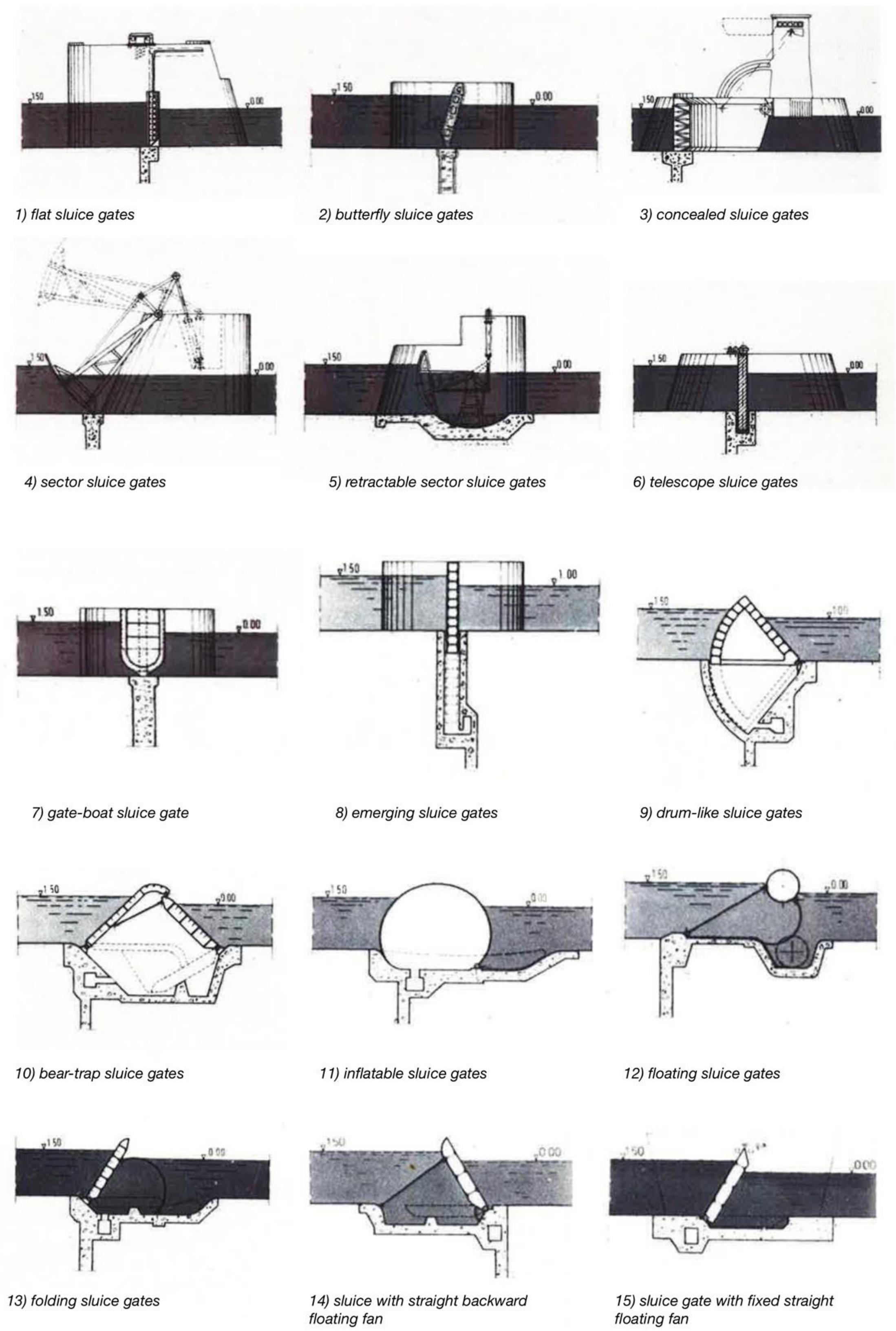


Figure 37 - Alternative barriers taken into consideration in the Progettone (Ghetti et al, 1981)

Many alternatives were considered with the special law in mind. Each is shown in Figure 37, through which the mechanism of each type can be easily extrapolated. The solutions have not been experimented further than the feasibility study conducted with the

Progettone. The set of requirements described above allowed the Sette Saggi to narrow the number of possible solutions to one feasible design. Based on the requirements, the following progressive elimination of alternatives led to the verdict.

Considering the requirements, designs 1, 2, 3, 4, 5 and 6 in Figure 37 have been excluded because they do not fulfill the requirements (A) (B) (C). These designs would require intermediate pillars, structures that emerge above the surface, or rails fixed to the bottom. Pillars are undesired because the section of the barrier would not remain intact and would not open to the flow of water in two directions, creating obstacles or dangers for boats in the case of fog or storm. Structures that emerge above the surface would set limits to the height of the ships and would block the view of the sea, which is undesirable due to the tourism industry. Finally, fixed rails would impose maintenance and protection problems that are not easy to solve in the open sea.

Type 7, 8, 9 and 10 and has been excluded because they each require long and excessively laborious maneuvers (7) or major submarine foundation works (8,9 and 10)

Types 11, 12, 13 have been excluded because they do not meet one requirement (D).

Solution 14 has been excluded as it operates in a position that would not mitigate the effects of the wave motion. Type 15 also was eliminated because it requires the presence of close pillars.

The choice was therefore restricted to type 16, a straight floating oscillating flap gates schematically represented in Figure 38 (Ghetti, et al., 1981). This type of barrier will then become the basis of the current Mo.S.E. barrier

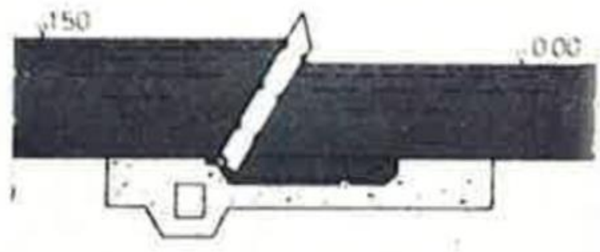


Figure 38 - Type 16, floating straight oscillating flap gates (Ghetti et al, 1981)

5.3.3 Mechanism of the barrier

The Mo.S.E. system is made up of arrays of sluice gates which, under normal tide conditions, lie completely submerged on the seabed of the three harbor inlets, hinged to the housings caissons. When a high tide is expected, the gates, emptied of water and filled with compressed air, rise up to emerge, creating a continuous barrier that divides the sea from the lagoon for as long as necessary. Ports connected to navigation locks allow the passage of boats when the barriers are raised. When the tide falls, the gates are again filled with water and return to their original position.

It is currently established that the barriers are put into operation for water levels greater than 110 cm as Venice is protected by raising banks and pavements (local defenses). However, the water level at which the flap gates are raised can be changed in relation to new needs or to different context conditions.

A total of 78 sluice gates will be built for the four arrays, the specifications of which can be found in the next paragraphs and illustrated in Figure 40. It will take about 4-5 hours to close the inlets, including the maneuvering times for lifting and subsequent lowering of the sluice gates (respectively 30 and 15 minutes). This system has been sized to support a difference in height between the sea and the lagoon of 2 m, or a tide of 3 m (currently the highest tide level recorded is 1.94 m); the flap gates are therefore able to cope with a significant increase in sea level. A schematization is given by Figure 39.

Flexibility of management allows the Mo.S.E. to cope with high waters in different ways: the simultaneous closure of the three ports, in case of exceptional events; the closure of one mouth at a time; and with partial closings of each mouth as the gates operate independently from each other. The third option would function against medium-high tides (Fantoni, 2017).

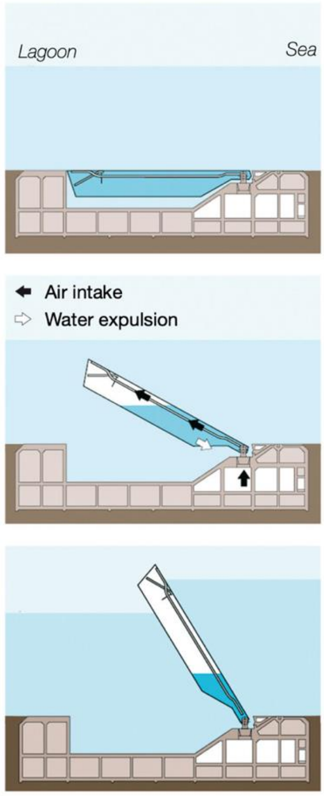


Figure 39 - Mechanism of the barrier

5.3.4 Composition of the Barrier

The barrier has a modular structure, meaning that is composed by many different elements. The first element to analyze are the caissons, upon which the mobile gates are hinged. A section of the central part of the barrier, displayed in Figure 40, describes each element within the barrier design (Ministero dell Infrastrutture e dei Trasporti, 2020).

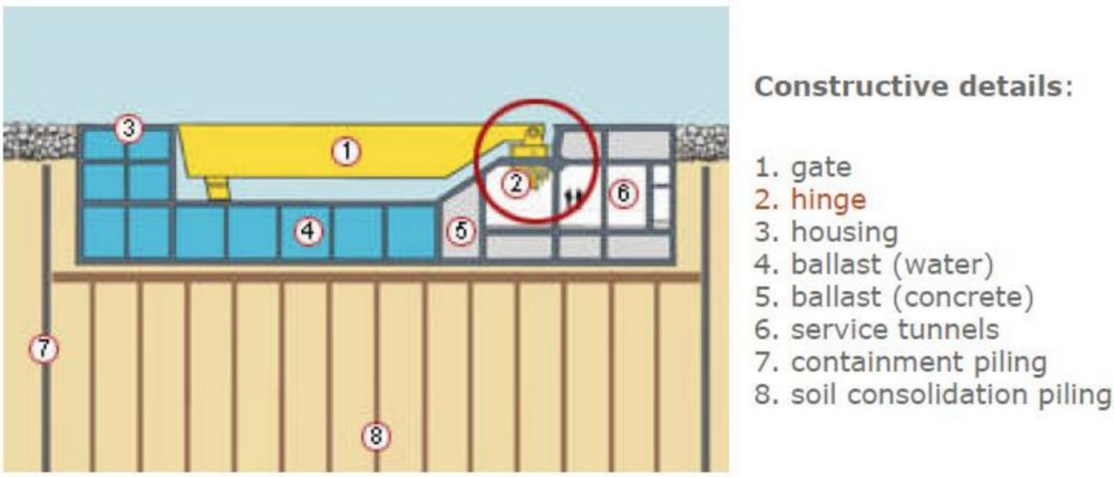


Figure 40 - Section of the barrier with construction elements (Lo Storto, 2015)

Caissons

Together with the mobile gates, the caissons are the main element of the Mo.S.E. system. They are multicellular concrete structures which, once completed and laid inside a submerged trench, will house the mobile gates and provide the operating tunnels. There are two kind of caissons: the housing caisson and the shoulder caisson. The first makes up the “bed” of the barrier, while the latter connects the housing caissons and the mainland. The shoulder caissons contain the vertical connections for the plant engineering and the workers. From a constructive point of view, the housing caissons are divided into many internal rooms organized on several levels and have the central part shaped to properly shelter the sluice gates. Each of the housing caissons contains 2 – 3 flap gates. Figure 41 shows both the Shoulder caissons (on the left) and housing caissons (on the right).

Figure 41 - Shoulder caisson on the left (LaPresse), Housing caisson on the right (CVN)

The dimensions of the housing caissons vary according to the length of the sluice gates that they must contain, which is proportional to the depth of the mouth channel (see Table 44). Unlike the housing caissons, the shoulder caissons are structures up to 28 meters high (in Malamocco) and have an area of 60 m by 24 m. A total of 35 caissons were realized (CVN, 2014).

Table 41 - Caissons specifications (CVN, 2014)

Barrier	Number of caissons	width [m]	length [m]	height [m]	weight [tn]
North Lido	7 Housing	60,0	36,0	8,7	13.000
	2 Shoulder	23,8	49,0	16,7	9.0000
South Lido	7 Housing	60,0	45,5	11,0	19.500
	2 Shoulder	24,0	60,0	25,0	15.000
Malamocco	7 Housing	60,0	48,3	11,5	22.500
	2 Shoulder	24,0	63,0	28,0	17.400
Chioggia	6 Housing	60,0	46,0	11,5	20.400
	2 Shoulder	24,0	60,8	24,5	13.000

The caissons must be resistant enough to provide the solid base of the barrier as they are equipped with sophisticated mechanical systems for the movement of the sluice gates. The technological heart of the gates is kept inside the long tunnels that cross the caissons from side to side to form a single tunnel connecting the shoulders of the flap gates. In the tunnels, electromechanical systems, communication and control systems are set up to operate the barriers including electrical systems, compressed air conducts, data transmission lines, and measuring instruments, from safety devices, fire systems, and many other components needed to properly operate the sluice gates.

Mobile Gates

The mobile barriers are made up of a series of mobile flap gates installed on the bottom of the lagoon mouths. They are defined as mobile gates since they are designed to raise above the water from their housing caisson built on the seabed. Each flap gate is made up of a metal box-like structure. Compressed air is pumped in, expelling water and raising the mobile gate on two hinges connecting it to the housing caisson. Using the buoyancy thrust allows the mobile gates of the barriers to maintain the difference in tide between the Venice Lagoon and the Adriatic Sea while swinging freely and independently due to the wave motion (CVN, 2014).

Each mobile gate has four fenders and rubber flaps. The fenders are designed to dampen the impact of the sluice gate on the body at the end of the demolition phase and to support the sluice gate when it is at rest inside the housing caisson. The rubber fins are arranged along the edges of the upper planking on the seaside (L-shaped fin) and lagoon side (P-shaped fin) and are designed to:

- reduce the air gap to limit the deposition of sediment in the compartment under the sluice gate, when the sluice gate lies at rest in the caisson;
- reduce the air gap on the sea when the barrier is raised, limiting the flow of water generated by the hydrostatic head between the sea and the lagoon;
- allow an operating margin during the removal and installation of the sluice gate, thanks to their elasticity, so as to avoid damage to the corners of the sluice structure and to the housing box in the event of maneuver inaccuracies.

They consist of a rubber compound, internally reinforced with vulcanized steel sheets (CVN, 2014). In total, there are 78 mobile gates plus 8 in reserve, consisting of 2 for each barrier. The specifications for the mobile gates at each lagoon inlet are shown in the Table 45 below (CVN, 2014).

Table 42 - Gates specifications (CVN, 2014)

Barrier	number of gates	canal depth	width	length	thickness	weight
North lido	21 gates + 2 extra	6 m	20,0 m	18,55 m	3,6 m	168 tn
South lido	20 gates + 2 extra	12 m	20,0 m	26,65 m	4,0 m	282 tn
Malamocco	19 gates + 2 extra	14 m	20,0 m	29,50 m	4,5 m	330 tn
Chioggia	18 gates + 2 extra	12 m	20,0 m	27,25 m	5,0 m	289 tn

Hinges

Each sluice gate is fixed to the base by means of two hinges on either side. In total, 156 hinge groups were produced for 78 sluice gates (CVN, 2014). The hinges of each flap gate have two points of attachment to the fixed structure and its mechanical connection must be removable to allow for maintenance and/or replacement. Coupling and uncoupling the hinges are mechanically operated by means of two hydraulic power units (one per each end of the hinge, where there are hooks) (Biraghi, 2014).

For each sluice gate the pair of hinges is necessary for the following reasons:

1. to tie the sluice gates to the housing caissons;

2. to allow movement of the sluice gates (lifting and lowering);
3. to ensure the connection between the sluice gates and the systems for the operation of the mobile barriers.

Each hinge is made up of three elements joined together: the male attached to the sluice gate, the female integral with the housing box and the tensioner (Paolucci G. M., 2012), shown in Figure 42.

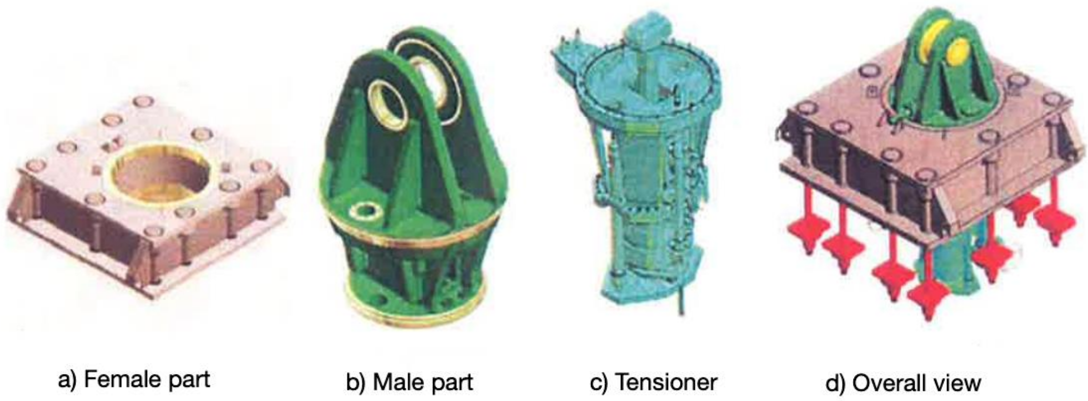


Figure 42 - Hinges elements and overall view (Palolucci, 2012)

5.3.5 Production, Assembly and Installation

The structures and systems take on different dimensions and shapes in proportion to the depth of the seabed, the width of the passage and the configuration of the existing works. The dimensions also consider the characteristics of the territory and the surrounding landscape. Given the different characteristics of the sluice gates in each of the sections (North Lido, South Lido, Malamocco and Chioggia), the construction and supply of the sluice gates were awarded with three different tenders (Scotti, 1994).

Grasshopper

A component known as the grasshopper is used for the installation of the sluice gates at the Malamocco port mouth. This vehicle was also used for the sluice gates of the Treporti canal. Fagioli has adapted the current grasshopper to the dimensions of the sluice gates to 29.5 meters long and 14 meters deep. The controlled sinking takes place through the gradual release of the cables. As it is lowered to the bottom, the sluice gradually fills with water. Once it reaches the level of the bottom, inside the hollow of the body, the sluice gate is connected to the body by means of the two male hinges, which are inserted and hooked to the females by means of the tensioning unit (CVN, 2017).

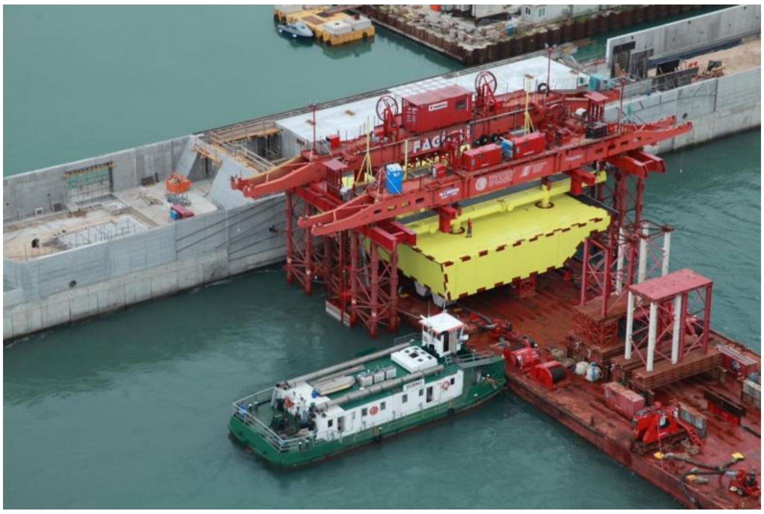


Figure 47 - The "grasshopper" vehicle (CVN, 2017)

Jack-Up

The Jack-Up Vehicle, shown in Figure 43, is the main machine used for the positioning, installation and removal for maintenance of the gates which are in the housing caissons on the bottom of the inlet passages. It is basically a self-lifting platform, specially designed for the Mo.S.E., with a modular hull equipped with retractable legs that are lowered during the maintenance and installation operation and raised during navigation. Two special cranes are anchored to the hull and connected to a special frame above which the gates are hooked. On its baptism in 2014, its engine failed, and one of the two legs broke when it entered in contact to the ground. Subsequently, the Jack-Up had many other technical fails related to its sailing ability. This problem not only raised the total cost of the project by €8 million to fix the machine, but it also let to delays to the general activities (CVN, 2015).

Initially, two of this special vehicles were to be built, but due to reallocation of the budget, only one Jack-Up was actually delivered (Cecconi, 2020).

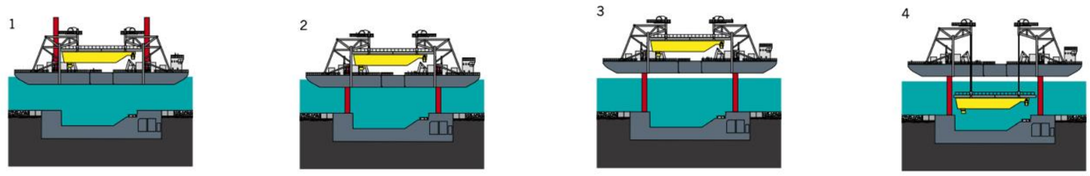


Figure 43 – Schematization of the Jack-Up vehicle (CVN, 2015)

5.4 The Mo.S.E. Barrier Operation System

The Mo.S.E. barrier, which will allow the isolation of the lagoon from the sea in case of danger, is designed to protect the lagoon's inhabited areas from any case of extreme flooding scenarios. The operational and closure activities of the MO.S.E. barrier will be managed from the Arsenal, located in the proximity of the historical center of Venice. Currently, it is unclear who will be in charge of the management of the barrier.

This chapter will investigate the operation system of the barrier, providing information about the closure levels, the systems of prediction of high tides and the closure criteria followed for the management of the barrier. This chapter aims to answer question RQ1.3, hereby repeated:

RQ1.3 Once completed, how and when will the Mo.S.E. barrier work?

5.4.1 Closure Levels and Relative Timeframes

The project indicates a half hour about to complete the entire closure process (D'Alpaos & Mel, 2017). In 2013, if was predicted an average number of 4 cases of high tide per year, for which the operation of the barrier would be needed. The average closing times of the barrier for each of these kinds of events, is estimated to be around 3 to 5 hours. The system is designed to upfront up to 3 m height gap between the lagoon and the sea. These indicators apply both under current condition and under conditions of sea level rise of a maximum of 60 cm (Cecconi, 2013).

The safety levels are found to be 110 cm for Lido and Malamocco and 120 cm for Chioggia. Chioggia is locally defended up to 130 cm as it presents different characteristics compared to the other two inlets. In case of forecasted high tide that exceeds the safety level of 110 cm, the port must be noticed three hours in advance. In such a case, the technicians in charge of management must position themselves in stand-by opposition within the caisson's tunnels, awaiting the arrival of the expected event. The system can consider the arrival of one or more repeated events. The forecast error is reduced as the high tide approaches (Cecconi, 2020). The levels are displayed in Figure 44.

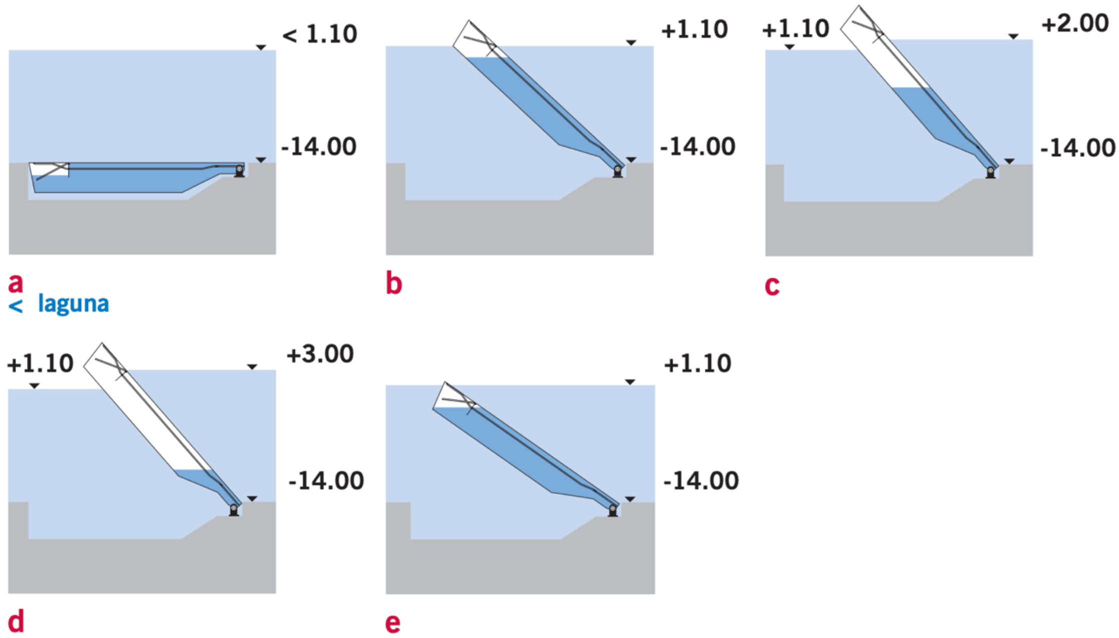


Figure 44 - Closure and operational criteria (Rosselli, 2008)

Chapter 3 includes information pertaining to the hydrological data of the Venice Lagoon and Adriatic Sea. Specifically, in Section 3.5, the classification system for determining the water level at which the Mo.S.E. barrier must begin to rise in order to reach the determined closure level of 110 cm is described. Research showed that this classification system was designed around a design storm with a return period of 10 years. Although this classification system used return period data, the determination of the closure level did not. Rather, the closure level was determined as a result of a compromise between several authorities working on the project.

5.4.2 Predicted Effects of Climate Change on Mo.S.E. Operation

The research in Section 2 suggests that, even at the closure water level of 110 cm, significant areas in the historic center of Venice are flooded. In order to defend Venice completely from every high tide, the Mo.S.E. would have to close at a level much lower than 110 cm, but this would result in the barrier system closing very often. If the barrier closed too often, especially in the autumn-winter season, then accessibility to the lucrative Venice port would be hindered and the economy would suffer. Furthermore, the water in the Venice Lagoon would filter less often into the Adriatic Sea, resulting in more stagnant water and possible environmental damage as a result of potential accumulation of pollution. The closure level of 110 cm was therefore determined to maximize the access to the port, prevent environmental damage and limit the Venice flooding to a maximum of

15% of the historic center. This limits the number of yearly closures to an average of five cases per year for an estimated total of 34 hours (Deputati, 1981).

Due to the rise in sea level as a result of climate change along with the sinking of the City of Venice itself, recent data shows that the frequency of occurrence of this water level is expected to change. Studies illuminated in Section 3.6 suggest that the return period of the closure level is expected to reduce from a range of 5 – 7 years to 2 – 5 years within the next century. However, existing research projects specifically investigating the change to the number of closures necessary to protect Venice from extreme floods was conducted and predicts a significant amount of closures proportional to certain levels of sea level rise. One study predicted that 300 – 430 yearly closures will be required for a sea level rise of 50 cm and the barriers will remain closed for a cumulative total of 1400 – 1800 hours per year. The below graphs illustrate the number of closures and time of closure as a function of sea level rise (Umgiesser, 2020)

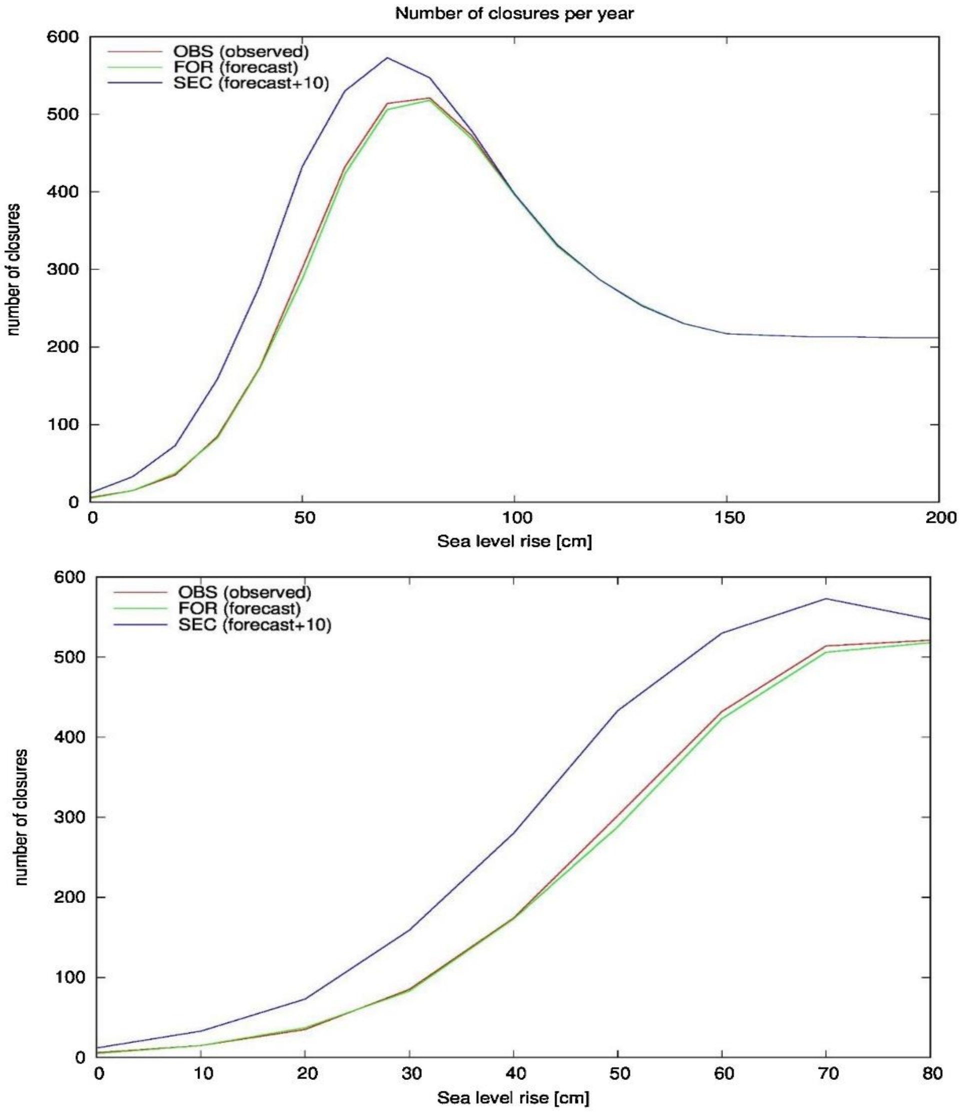


Figure 45 - The number of closures of the Mo.S.E. barrier is illustrated in the above figures as a function of the sea level rise. The above graph indicates that the number of closures levels off after a sea level rise of about 75 cm. (Umgiesser, 2020)

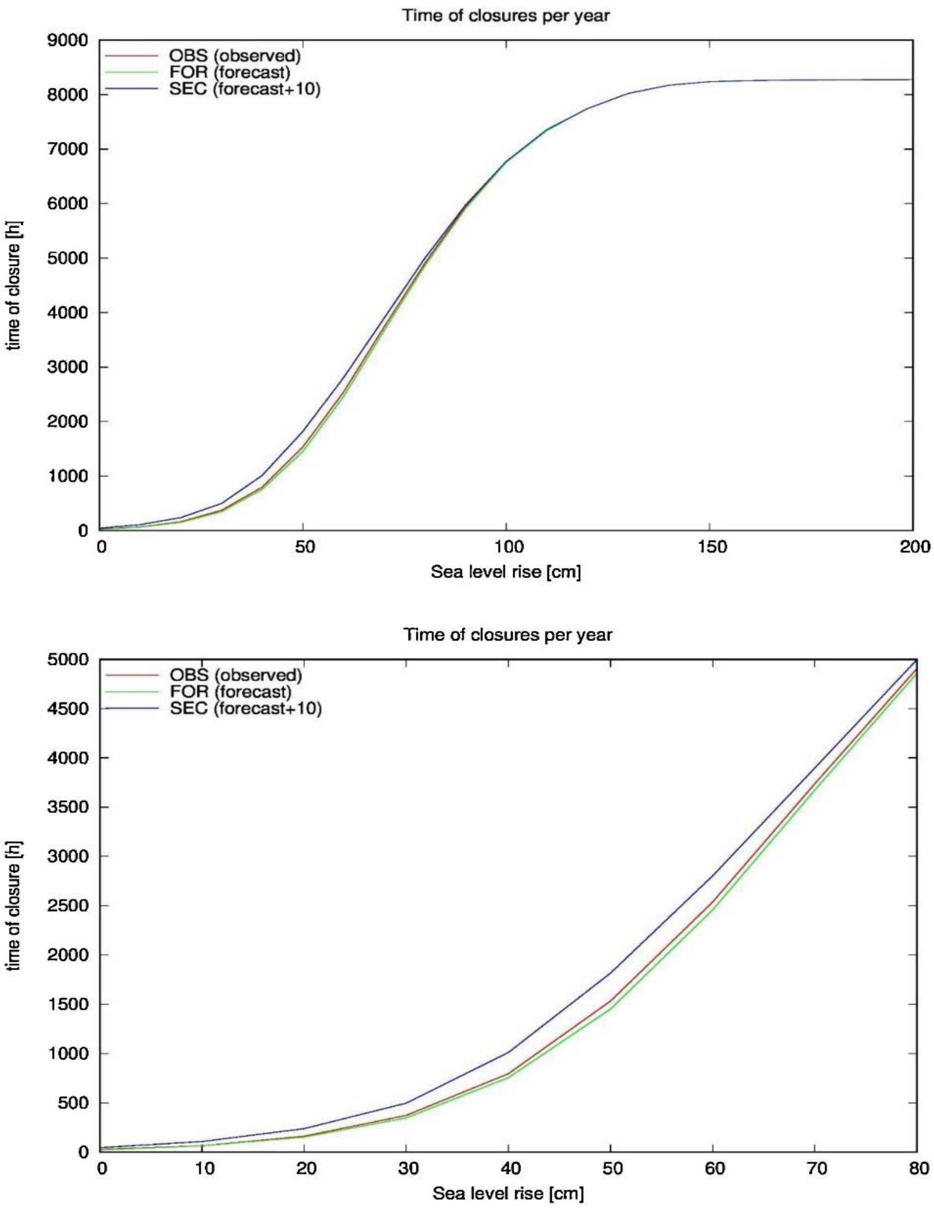


Figure 46 - The figures illustrate the cumulative yearly closure time of the Mo.S.E. barrier as a function of sea level rise. (Umgiesser, 2020)

The graphs in Figure 45 indicates fewer individual closures of the Mo.S.E. barrier after about a sea level rise of 75 cm, but the graphs in Figure 46 indicates a steady increase of the cumulative closure time without a peak. This implies that, after a sea level rise of 75 cm, one individual closure would have to last long enough to prevent several extreme water level events from entering the Venice Lagoon. Figure 46 also indicates that, after a sea level rise of about 130 cm, the Mo.S.E. barrier would have to be left permanently closed (Umgiesser, 2020).

Although sea level rise may not reach the level that necessitates permanent closure in the foreseeable future, data pertaining to climate change strongly suggests that the rise in sea level will result in the Mo.S.E. barrier closing more often than for which it was designed. However, because the Mo.S.E. project not yet completed and the design is adaptable, there are still many chances to update the design to increase its effectiveness.

5.4.3 Management System of the Mo.S.E.

The effective decision to close the barriers is based on the direct measurement of the water level and not on expected data. The forecasts are used to establish the alert about the possible occurrence of a forthcoming high tide event, but it is the actual survey in the field that provides the decisive information regarding the operation of the barriers. In particular, the management procedures have established that the barriers are raised when the water reaches certain predetermined levels which vary according to a progressive succession from the lowest one (in case of more intense events) to the higher one (for less critical events). These criteria are elaborated upon in Section 3.5.

The management system of the Mo.S.E. barrier involves three principal subsystems, further explained in the next sub-paragraphs:

- Monitoring of the climatic sea conditions
- Forecast of high tides
- Support system of managerial decision-making

Monitoring of the Climatic Sea Conditions and Forecast of High Tides

To check the evolution of the trend of the tide in real time, a network of tide gauges is used. The network transmits the water level data, collected in the lagoon and the three inlets, every 5 minutes. At the same time, local winds and rainfall values are also measured in the lagoon and on the watershed, calculating the total volume of water delivered to the lagoon. The information is organized and made available in the database and is continuously verified both in order to be immediately used by the high tide forecasting models, and to proceed directly to the decision to close the port mouths with the barriers. The monitoring system acquires the data measured by the networks of the Interregional Department for Public Works and by other bodies and institutions with which collaboration agreements have been previously made[7]. The data are transmitted by multiple different means, including cable, radio, online website and mobile phone.

As part of the management of the Mo.S.E. (CVN, 2014), the high tide forecasting system is used for the operational alert 36 hours in advance, with respect to the occurrence of high tides that may require the lifting of mobile barriers. During the alert phase, the intensity class of the event and the corresponding closing level are defined according to the maximum level envisaged, increased by 20 cm to guard against possible errors in the forecast. With the alert procedure, the maneuver to put the Mo.S.E. gates in operation should be carried out with the advance notice necessary for the safety of port traffic and naval surveillance and rescue vehicles (Cecconi, 2013).

Support System for Managerial Decision-Making

The IT decision support system allows for the implementation of the decisions involving the barriers closing and reopening maneuvers, i.e. when and for how long to operate the Mo.S.E. flap gates. The decision support system uses high water forecasts, measured tide level data and data relating to the rise in water levels in the lagoon during the closure of inlets. Through special consoles, the simulation and analysis procedures, the lifting or lowering orders of the sluice gates and the signaling and communication services to the other interested subjects are controlled. Mathematical models are crucial for

[7] Aeronautica militare, Arpa Emilia Romagna, Arpa Veneto, Protezione Civile del Veneto e del Friuli Venezia-Giulia, Istituzione centro previsioni e segnalazioni maree del Comune di Venezia, CNR – ISMAR

understanding management rules and accurately simulating the behavior of such a complex system, conditioned by the many variables involved in the decision-making process relating to closing operations. The use of the models allows real verification experiments and progressive improvement of the quality of the computerized management structure of the Mo.S.E. and in particular of the procedures and data necessary to manage any situation, including unexpected events (CVN, 2014). The installed computers present in the office provide continuity in case of failure of one or two computers, however the risk of damage by flooding, fire and hacker attacks still threatens the safety of the software. A "Disaster Recovery" software system is updated constantly and kept safe in a monitored position (Cecconi, Interview, 2020).

Control Room

The Mo.S.E. barriers will be controlled by the central operating room inside the control room, where all the information necessary to guarantee the control of the water level in the lagoon will be received. This information includes the following:

- monitoring and weather forecast;
- coordination communication with the competent territorial bodies (Port Authorities and Port Authorities of Venice and Chioggia, lagoon Municipalities, etc.);
- the state of the electro-mechanical devices for lifting the sluice gates and control devices.

The control room is an entity separate from the central operating room, but they are constantly in communication. In anticipation of a high-water event, the central operating room of the Arsenale will issue commands to the operating rooms of each lagoon mouth that operate the sluice gates. To ensure a safe control of the water level, the Mo.S.E. management system uses the best knowledge available on the physics of the meteorological-marine processes of high water generation in the Adriatic and of the propagation of the tide in Venice, developed over twenty years of activity (Cecconi, 2013).

5.4.4 Failure Probability

The risk that one out of the total 78 gates will not function is 1/10000, or 0.01%, per closure per gate (Cecconi, 2020). However, reliable forecasts indicate that operational failure of up to 2 gates does not cause problems depending on the duration of the event. The safeguard threshold can be exceeded in the city even in cases of intense rain or in places where the slope of the sidewalk allows flooding of about 5 cm. Depending on whether the threshold is acceptable or not, money can be saved and damages can be prevented (Cecconi, 2020). The failure of the barrier in case of emergency is also related to other important factors linked to connection, power scarcity and fire or flooding of the control room. (Cecconi, 2020)

5.5 The Mo.S.E. Project Management

This chapter focuses on the management of the Mo.S.E. project, going into detail about what concerns the internal organization of the CVN and the construction of the barrier. The chapter will first look into the stakeholder involvement, and will then focus on the CVN, contractor of the management and implementation of the works, highlighting specifically the governance of the company and how the object was handled from their perspective. This will answer question RQ2.1, hereby stated:

RQ2.1 Who oversees the Mo.S.E. project and how is it handled?

For the peculiar nature of the project, upon the basis provided by the General Works Plan, the design and the implementation of the barriers were subject to frequent changes and corrective measures throughout the construction of the Mo.S.E. barrier, with each convention resulting in a new update to design and construction.

A clear definition of the stakeholders involved and their position within the project is defined in the next paragraph, focusing on the contractor, CVN, and its governance in the subsequent chapter.

5.5.1 Stakeholders Involved

In a mega project, like the present one, the complexity of stakeholder configuration goes beyond a single report. Therefore, in the current studies, a sample of the numerous stakeholders will be evaluated in order to provide a conceptual representation of the management of the project.

A brief introduction to the external main stakeholders involved in the implementation of the project, their attitude (positive/negative) towards the project and the relative influence they have on the project will follow. The stakeholders are hereby subdivided into Regulatory Agencies, National Government bodies, Local Government bodies, external stakeholders, Green Opposition and International Involvement.

Regulatory Agencies

ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale (*Lit. Superior Institute for the Protection and the Environmental Research*) validates and controls the environmental monitoring activities, evaluates environmental data released and checks if environmental targets are met. The institute has a positive attitude towards the project.

In April 1999, the European Commission (EC) issued the resolution on the crisis in Venice, calling on the Italian government to decide on how to proceed to the final design phase of the project by the end of the year. In December 2005, after complaints from some environmental movements, the EC started the infringement procedure related to the lagoon habitat pollution, because the environmental section of the EC expressed its belief that the Italian government had not planned effective mitigation measures to preserve wild bird habitat and migration patterns. However, the EC had an overall positive attitude towards the project (Luciano Mazzolin, 2015).

The Corte Amministrativa Regionale (TAR, *Lit. Administrative Regional Court*) and Juridical State Council (JSC) had lodged, in total, 9 legal petitions related to environmental issues. All claims have been rejected, making both of these stakeholders favorable to the project. On the grounds of breaches of procedure and substance, the TAR issued a ruling annulling the December 1998 decree of negative environmental impact of the Ministry of the Environment. TAR also rejected all the appeals made against the MO.S.E. system by a number of bodies such as WWF, Italia Nostra, and Provincial Authorities (Fregolent, 2014). Lastly, in 2000, The TAR for the Veneto cancels the negative environmental compatibility decree of the project issued by the Minister of the Environment for method and merit issues, in consultation with the Minister for Cultural Heritage and Activities (CVN, 2014).

National Government

The Ministry of the Environment (ME) opposed the project in the first stage of development, until further efforts and mitigation measures were taken. In 1998 the ME Environmental Impact Assessment Commission expressed a negative opinion regarding the environmental compatibility of the design (Barlassina, 2014). The Comitatone considered various opinions expressed during the extraordinary Environmental Impact Assessment (EIA) of the design for mobile barriers at the lagoon inlets. In a resolution, the committee unanimously delegated the water authority to undertake directly wherever responsible, or to coordinate a series of interrelated in-depth studies with other groups wherever needed to be completed by 1999. The Comitatone also called for the rapid set-up of a specific Planning Office in collaboration with the competent administrations in the hopes that this office could be set up in time to enable it to participate in the review of the general Plan of Interventions (Lo Storto, 2015).

The Ministry of the Cultural Heritage (MCH) supported the project. Its Central Office for the Environment and Landscape in 1998 expressed a positive opinion regarding the design for mobile barriers, with certain provisions (CVN, 2014).

The Ministry of Public Works (MPW) and The Ministry of Infrastructure and Transport (MIT) were the promoters for the MO.S.E. project, therefore their attitude towards the project was very positive and succeeded in influencing the project by stimulating its process (High Council of Public Works, 1999).

The Committee for Policy, Coordination and Control (also known as the Comitatone) of all measures for the safeguard of Venice is the body for policy, coordination and control of the objectives established by the special legislation Law 798/84. The committee was supportive of the project and also stimulated its process.

Local Government

The Municipality of Venice (MV) was overall sympathetic to the project. However, it held some concerns about the construction of the facilities. In late 2006, after the change of the political council of the City of Venice, the new political administration opposed the MO.S.E. system, asking for the evaluation of a number of solutions indicated as alternatives (CVN, 2014). The Council of Ministers of the Italian Government, after taking into exam the requests from the local authorities and the results presented in a report on project progress and the opinions of major stakeholders, retained that no new elements have emerged requiring the original project to be modified.

The Municipality of Chioggia (MC) was also in favor of the project.

Veneto Region (VR) had a positive attitude towards the project too, giving the approval of the full Veneto Regional Technical Commission to the design.

Environmental Parties

Environmental opposition to the Mo.S.E. has taken various forms as political conditions have changed. Although the environmental parties have enjoyed little success in general elections, it would be a mistake to ignore how they have influenced public policy on issues such as the mobile barriers (Standish, 2003).

The Italian World Wildlife Fund (WWF) and conservationist Italia Nostra party (*Lit. Our Italy*) promote the idea that Venice may soon be inundated because it will be subjected to rising sea levels from climate change. However, the Italian Green Party (GP), working with these environmental groups, has also delayed the Mo.S.E. project (Standish, 2003).

International Involvement

While the protection of Venice is an effort undertaken by Italy and implemented in large part by CVN, international experts have also played important roles. From the US, engineering experts from the Massachusetts Institute of Technology (MIT) and scientists from Scripps Institution of Oceanography (SIO) have been involved at different times in various aspects of the endeavor to save Venice (Deheyn & Shaffer, 2007).

From the drafted stakeholder analysis drawn, it was possible to compose the following Figure 47, which allows to visualize the different stakeholders on a power/Interest grid.

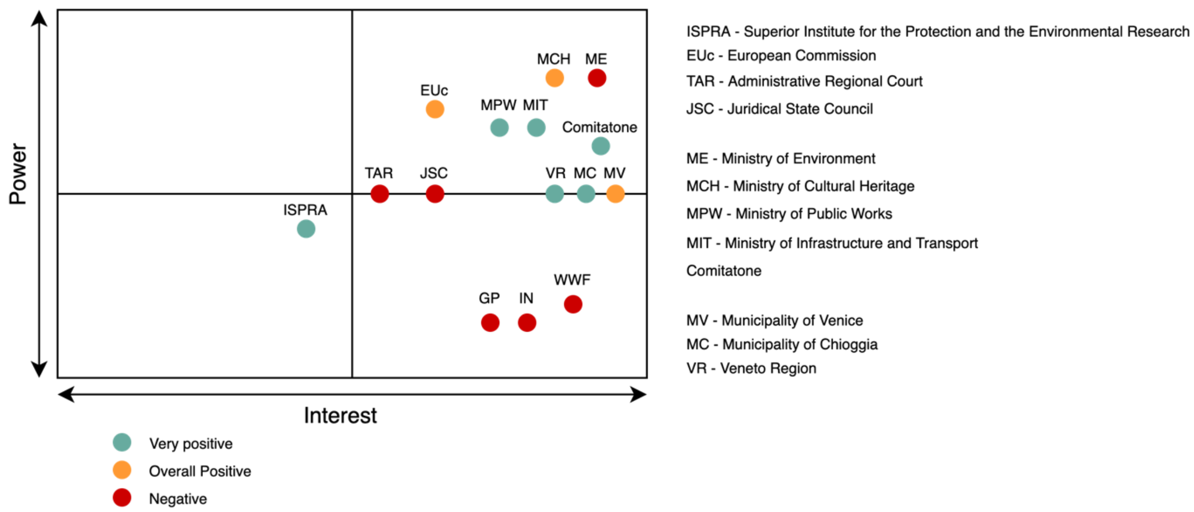


Figure 47 - Stakeholders power/interest grid

5.5.2 Consorzio Venezia Nuova

The Venezia Nuova Consortium (CVN) is a consortium of local enterprises commissioned to the state (specifically the MPW and MoW) to realize and coordinate the works planned to assure the safeguard of the City of Venice and the Venice Lagoon, with respect to the Special Law 789/84. The CVN was established in 1982 by four companies: Italstrade (50%), Grandi Lavori Fincosit (25%), the Società Itaiana per Condotte d'Acqua S.p.A. (20%) and General Construction Company Mazzi (5%).

Since the establishment of the CVN took place roughly 38 years ago, and the composition of the consortium varied significantly over time the responsibilities of each company within the Venice Project and with respects to this last, is unclear or most likely confidential. With the progression of the years, the latest composition of the CVN relates to 2019, showed in Table 43, along with relative share percentages:

Table 43 – Member and Investee companies within CVN in 2019 (CVN, 2019)

Member companies	
Consorzio Coopertaive Costruczioni - C.C.C. Society Cooperative	5,1095%
Consorzio G.R.V. - Grandi Restauri Veneziani	0,0949%
Consorzio Italvenezia	17,5547%
Consorzio Venezia Lavori - CO.VE.LA S.c.a.r.l.	25,4401%
Grandi Lavori Fincosi S.p.a.	0,9600%
High Tide S.c.r.l.	29,348%
Impresa di Costruzioni E. Mantovani S.p.a.	3,3212%
Kostruttiva S.c.p.a.	2,6332%
San Marco, consorzio costruttori veneti	13,1661%
Società Italiana per Condotte d'Acqua S.p.a.	2,3723%

Purpose of the CVN

Under a concession or contract, the purpose of the consortium is to carry out the interventions promoted by the state administrations as well as the central and local public bodies for the protection of Venice, in particular the works regarding the following:

- the regulation of the sea levels in the lagoon;
- the lagoon shores;
- the port works in Venice and nearby areas;
- the maritime works and coastal defense;
- the reclamation, consolidation and arrangement of bridges;
- the foundations for the mobile barrier in the canals
- the arrangement of natural and artificial waterways.

In 1982, the duration of the consortium was first established at 10 years, with the possibility of proposing with unanimous resolution of the consortium members in relation to the computation needs of the consortium's object.

Governance and Division of Work

In order to carry out its duties as a state concessionaire for carrying out studies, experimental activities, designs and works, the CVN has over time equipped with a planning, organization, management and control structure for the various safeguard interventions in the various implementation phases. CVN acts, at the same time, operationally, as an interface with the granting administration on the one hand and with the executors of the activities on the other. The CVN followed, therefore, the development of the interventions, from their definition in the context of contracts with the granting authority, to their design, to their completion (Filippi B. C., 2016).

Since the establishment of the CVN took place roughly 34 years ago, and the composition of the consortium varied significantly over time the responsibilities of each company within the Venice Project and with respects to this last, is unclear or most likely confidential. Many of the works were tendered to various companies, often international, such as construction or the instalment of the gates and the caissons at the three different lagoon mouths.

Grandi Lavori Fincosit S.p.A., a member company of the consortium, was responsible for building a total of 18 caissons for the mouth of South Lido and Malamocco (Barocco, 2014). The caissons were built in the construction site of Malamocco and the immersion of the caisson was different from Chioggia. The caissons were built on the prefabrication square located south of the port mouth on the island of Pellestrina. Here, the launching of the caissons themselves took place with the use of the Syncrolift[8]. To allow the transit of ships and boats during all the phases of laying the caissons, the navigation basin was made operational, designed to ensure the passage of large ships even when the sluice gates will be in operation.

Clodia Scrl was responsible for the construction of the caissons for Chioggia inlet. Strukton Immersions, a Dutch company, was responsible for engineering, transporting and immersing eight concrete caissons in Chioggia. Throughout the procedure, the immersion positioning was tendered to Geocon and the diving work was tendered to OTN Company.

The first 21 sluice gates (+2 extra) for the North Lido barrier were built by the Italian company Cimolai S.p.A. in Montefalcone, Italy. The production of the other 57 sluice gates (+6 extra) was awarded to the Brodogradevna Industrija Split d.d. company in Split, which built the 19 sluice gates for the Malamocco barrier, 18 for the Chioggia barrier and 20 for the South Lido barrier.

The transport of the sluice gates took place by sea, on pontoons pulled by tugboats. The first 21 sluice gates of the Lido Nord barrier arrived from Monfalcone. The other 57, destined for the barriers of Malamocco, Chioggia and Lido south, arrived from Split, Croatia, on special pontoons that transported four of them at a time. Before the installation, the mobile gates were temporarily stored to allow the assembly of the "male" hinges. The first 21 sluice gates of North Lido were assembled in the "ex Pagnan" area in Porto Marghera, while the other 57 were stored and fitted with hinges in the shipyard at the Malamocco lagoon mouth.

For the installation of the sluice gates of Lido Nord, Chioggia and Malamocco, a launching vehicle, a metal "grasshopper" was used, while in Lido Sud they were crouched to the caissons with the special Jack-Up MO.S.E. I vehicle, both described further in the following segments.

Initially, two of these special vehicles were to be built, but due to reallocation of the budget, it was decided to build only one Jack-Up. The Verona's company who designed the machine, "Technital", was part of the former CVN member: MAZZI group.

A representation of the contracting scheme, sampled to a limited number of contractors, is display in Figure 48.

[8] A specific system for the immersion of the caissons realized by Rolls Royce Naval Marin inc. located in Annapolis (USA).

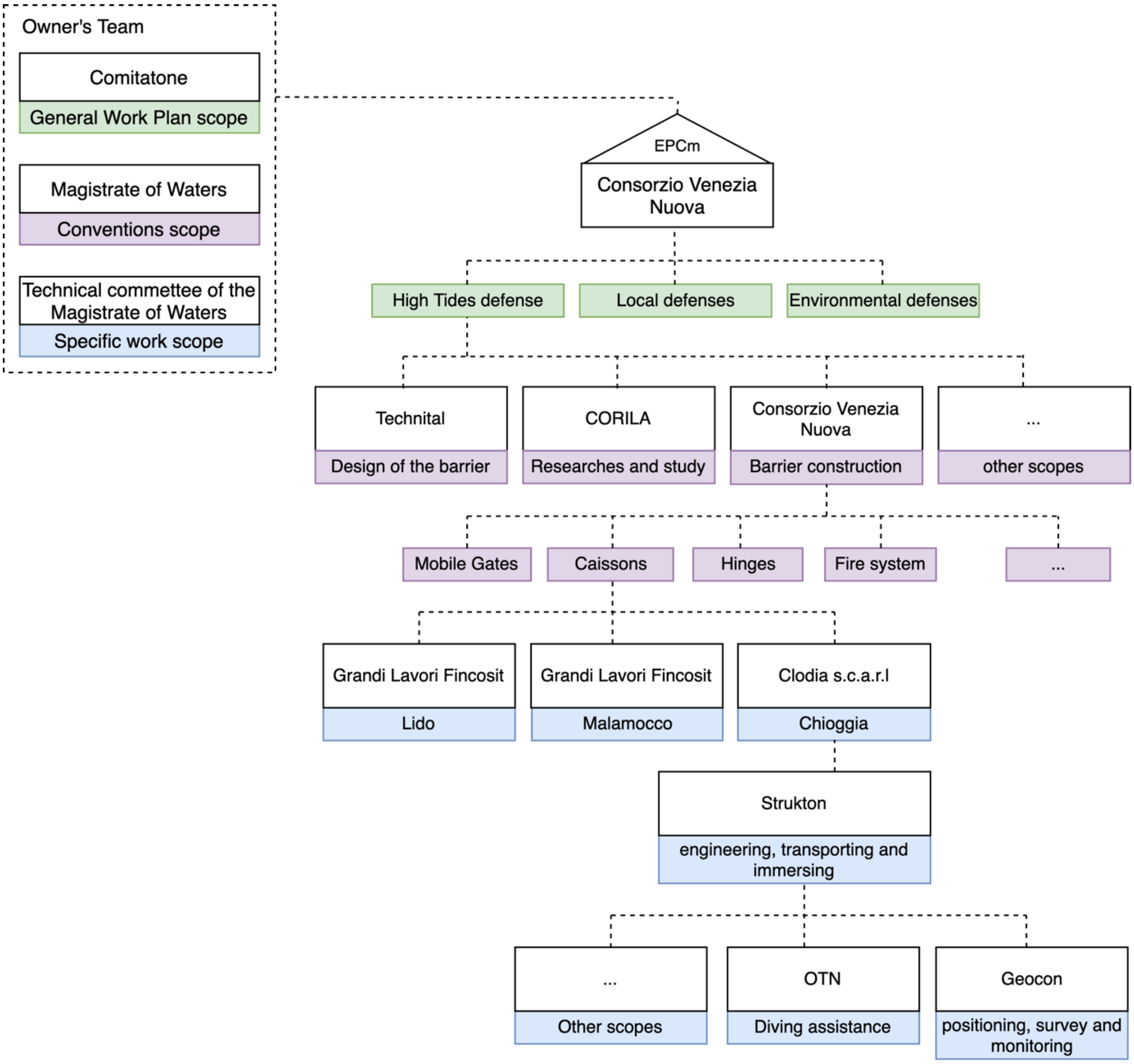


Figure 48 - Sampled contracting scheme

5.6 The Mo.S.E. Project Performance and Delays

The Mo.S.E. project suffered many technical and organizational problems throughout its implementation process. Many of the delays causes and related information are provided by Dr. Ir. Giovanni Cecconi, through a video-conference interview. In 2014, the project was affected by several corruption issues, by both the governmental entities and the private companies involved in the Mo.S.E. works, that led to the opening of several trials.

This chapter will firstly focus on the major delays that influenced the project process until 2019. Subsequently, the Mo.S.E. legal issues will be discussed by analyzing the complexities that are affiliated to the project, highlighting the causes that allowed the inconvenience to occur and the effects that it had on the total duration of the project. This chapter's goal is to identify the status and circumstances during the 2019 Venice flood event in terms of project completion, giving answers to the research question RQ2.2 and RQ2.3, going as follows:

RQ2.2 What are the complexity variables that can be associated to the Mo.S.E. project?

RQ2.3 What were the most severe delays suffered and which were the causes behind them?

5.6.1 Complexity Analysis of the Mo.S.E. Project

The Mo.S.E. project can be compared to many other large infrastructure projects, in which complexity is one predominant factor. Therefore, it should be kept in mind that:

- There is a plurality of external "participating" subjects: the decision-making, control or authorization processes, the identification of the purposes and the definition of the priorities are carried out by different parties.
- There is a plurality of internal "participating" subjects: the execution of the interventions is entrusted to the various consortium executing companies; the technological content of the activities, in addition to being completely innovative in some cases, must be applied to particular and delicate situations.
- A large number of projects are carried out in parallel by creating interactions with each other and also, in some cases, with other activities falling under the competence of different bodies; the Venice Project is made up of conceptually and functionally different works distributed over a vast, heavily populated area, with unique natural features.

This already complex situation must include a component of "uncertainty;" since it is not possible to know the total or annual value of the financial resources that will be allocated by the state for the interventions under concession, nor at the time when there may be their actual availability, the planning must be carried out assuming different operating scenarios (Doni & Signorelli, 1997).

Bruijn et al. (1996), conducted a study in which the three dimensions of complexity – Technical, Organizational and Social - were defined (de Bruijn, Jong, Korsten, & Van Zanten, 1996). Bosh-Rekveldt et al. (2010) applied the three dimensions to large infrastructure projects, developing a Technical, Organizational and External framework (TOE framework) to assess the level of a project complexity. The framework can be used to define which dimension is most complex, in order to adjust management strategies and deliver a better result. In this paper, the TOE framework is applied to the Mo.S.E. project to assess its complexity level. The framework consists in 17 technical aspects, 17 Organizational aspects and 13 External aspects (Bosh-Rekveldt, Jongkind, Mooi, Bakker, & Verbraeck, 2010). A full extension of the framework can be found in Appendix L, along with its results. As complexity is mostly a subjective process, the framework was compiled from the CVN perspective as a company. In spite of the fact that the used criteria have reason to be, the results generated are to be considered completely hypothetical. Some of the aspects have a high level of subjectivity in them, those are kept moderate and neutral, otherwise established in line with verified events.

The technical section of the framework scored 67/85 points, the Organizational part 55/85 points, while the external aspect scored 43/65 points. Hence, according to the TOE framework, the Mo.S.E. project complexity is characterized at the most by External (39%) and Technical complexity, rather less instead in Organizational complexity (24%).

Locatelli et al. (2017) suggest that specific features of construction projects might make it more susceptible to corruption. Two of the features identified, along with uniqueness, size and project complexity, are found to be number of contractual links and government involvement. The first is identified because “public administrators can use their arbitrary power especially where there are insufficient controls on how government officials behave” and the latter because “each contractual link provides an opportunity for someone to pay a bribe in exchange for the contract award” (Locatelli, 2017).

5.6.2 Major Delays in the Construction Until 2019

An interview conducted with the former control room director of the MO.S.E. barrier, Giovanni Cecconi, gave insight in the main causes of delay and incidents for the construction for the barrier. An extended version of the interview can be found in Appendix N.

After an experimentation phase, construction of the barrier officially started in 2003 and was initially scheduled for completion in 2012. In 2014, a large investigation discovered a large amount of corruption on the project for which the former president of the Veneto Region Giancarlo Galan and several others were arrested and sentenced for 2 years and 10 months of jailtime (Il Post, 2014). Following the legal investigation, the project has undergone an abrupt slowdown and the commissioner management of the MIT has not complied with the need for rapid completion of the work (Senato della Repubblica, 2019). The execution of the works was then entrusted to the CVN with an extraordinary management and anti-corruption system.

The activity regarding the completion of the electromechanical works, such as the assembly and installation of the hinges, sluice gates and definitive plants was originally planned for completion by the end of 2014 but has been delayed for more than 5 years. In those 5 years, the project progress was only 5% of the scope, likely due to the confusion following the scandal and the arrests. In those years, the Magistrate of the Waters was abolished and replaced by the Provveditorato Interregionale per le Opere Pubbliche per il Tri-Veneto (PIOPTV, *Lit. Provincial Authorities for Public Works for Veneto, Trentino Alto Adige and Friuli Venezia Giulia regions*). For these activities, in the last years, the main cause for delay then consisted of corruption and high government dependency and involvement (La Repubblica, 2019).

In 2015, while one of the caissons in Malamocco inlet was undertaking finishing works, a tunnel was flooded, damaging the pipes which needed immediate replacement, having been immersed in salt water (Cecconi, 2020).

One of the main technical problems concerned the navigation lock of the Malamocco Inlet, in November 2019. During the design, it was not considered that the lock was subject to wave motion, and therefore was not been shaped to resist the wave forces effectively. The lock was designed to close in two minutes, so it should not interfere with port traffic. The error was derived from a miscommunication between the commissioned design company and the contractor. No one reportedly communicated to the commissioner that the prefabricated lock differed from a fast navigation lock for rivers, given its exposure to wave motion, so the latter was not considered (Cecconi, 2020). Lack of communication and transparency for the scope and job description can be considered as a major cause of delay.

Lastly, abnormal vibrations of the tubes were registered in the Malamocco Inlet in late October, causing the testing of the completed barrier, originally scheduled for November 6, 2019, to be delayed. The delay in the barrier final test was later considered motivation for why the barrier was not operating during the 2019 flood event (La Repubblica, 2019).

Over the years, CVN often complained of delays in the granting of the funding necessary to proceed with the works. The European Commission, in charge of progressively financing the project, apparently was reluctant to commit many of the demands made by the CVN. This kind of delay mostly likely also contributed to the general delay of the project.

5.6.3 MO.S.E. Scandal

With the accusations made by the public prosecutors of corruption, tax fraud and illicit financing of the parties, a judicial investigation on the Mo.S.E. project started on 4 June 2014 (Marchina, 2019). On the same day, the prosecutor of Venice made 35 arrests and announced on the local news that at least a hundred people were placed under investigation for corruption and bribes related to the Mo.S.E. construction project. Giovanni Mazzacurati, now deceased, started a collaboration after his arrest in 2013.

The magistrates of the Venice prosecutor's office had long been investigating the economic activities around the Mo.S.E. In 2009, a tax audit was ordered against one of the companies engaged in the construction of the barriers, suspected of having issued some false or inflated invoices to accumulate money in some accounts abroad to be used later to bribe officials and politicians in Italy

The charges are many, according to the people involved. The most frequent charges contested by Venice prosecutors were related to corruption, tax fraud and illicit party financing. According to the power of attorney, the mechanism for obtaining the money used in bribery of political officials was that of false or inflated billing (Il Post, 2014).

Corruption Causes and Effects

The 1991 Memorandum of Understanding between the Magistrate for Venice Waters and the CVN can be considered the formal start of the project. The signing took place only some months before the European regulations on contract awards took effect, allowing companies registered in other EU countries to run for open tenders. The contract expressly established that work can be subcontracted without conducting any public bidding. This would create the space for corruption that developed for over two decades and allegedly took a major cut from the Mo.S.E. budget (Tijhuis, 2017).

In addition, research shows how corruption can affect mega-projects and set government involvement as one of the main factors that allow the corruption mechanism, even in countries that do not often experience corruption, along with the size, complexity and uniqueness of the project (Locatelli, 2017). The corruption taking place in this case was most likely due to the public nature of the project. Since the Italian government was the only financial provider for the project, certain members of the ministries and companies involved in the project saw the project as an opportunity to collect state money for their own personal benefit. In an attempt to restart the project in 2014, the Prime Minister Renzi sent three commissioners with the task of managing the continuation of the work, but the disputes with the contractors continued to block the construction progress (Tonacci F. , 2019).

New Anti-Corruption System and Temporary Governance

Since the MO.S.E. scandal took place in 2014, the management system of the CVN was re-established by the National Anti-Corruption Authority (ANAC). Under determined circumstances, this authority is entrusted with the responsibility to reassert a proper management structure to allow the project to continue its implementation without further ado. This was done by appointing a maximum of three extraordinary administrators who must hold the necessary requirements and experience to carry the responsibility (Pecoraro, 2014). Under the conditions, the CVN was then entrusted to the supervision of two administrators, Doc. Luigi Magistro and Prof. Francesco Ossola,; then later to Supervisor Attorney Giuseppe Fiengo until the completion of the works. In 2020, Doc. Luigi Magistro resigned from his position and Attorney Vinenzo Nunizata took office (CVN, Consorzio Venezia Nuova - Amminisrrazione Trasparente, s.d.).

5.7 Status of the Mo.S.E. project during the 2019 flood event

On Tuesday, 12 November 2019 at night, the high water level in Venice reached 187 cm, approaching the levels of the highest ever recorded, 194 centimeters, which was reached during the flood of 1966. The tide then gradually lowered, but on 13 November, there was a new tide peak of 160 centimeters at about 10:30 in the morning, as predicted by the city's Tide Forecasting and Reporting Center. The Municipality of Venice ordered the closure of all the schools in the historic center, the islands of the lagoon, the beach and Pellestrina and announced that it wanted to declare a state of emergency (Il Post, 2019).

This chapter will provide an overview of the project performance up until 2019, analyzing the project status during the 2019 flood event. A special paragraph, at the end of the chapter, is dedicated to the evaluating whether the barrier would have prevented the flooding and the related enormous damage suffered if it were fully functional. Through these paragraphs, the chapter aims to answer RQ3.1 and RQ3.2, stated again as follows:

RQ3.1 What were the circumstances of the 2019 Venice flood event in terms of project completion?
RQ3.2 In relation to the flood event of 2019, what were the reasons behind the decision of not operating the barrier?

5.7.1 Project Performance until 2019

Up to the time of the November 2019 event, many works meant to protect the lagoon were completed as part of the mega-project REA. For example, the coasts and the outer piers were strengthened and the defenses against the sea or low walls which had been swept away by the waves in 1966 were restored and raised. The banks of the rivers which the 1966 flood had overcome by spilling into the lagoon during the flood were raised In Venice and the major islands. Gas, electricity, water and telephone exchanges have been raised to a safe level; the most exposed ground floor dwellings have been protected or eliminated; oil heating has been eliminated; sewage treatment plants and protection tanks have been installed; civil protection was organized and a forecasting and early warning service for high tides was set up.

The works concerning the Mo.S.E. project, on the other hand, were completed only by 95% at the time, i.e. a delay in completion of almost 8 years since the 2012 initial deadline. The new completion date scheduled is the end of 2021. A table summarizing the latest and most important future dates in the project construction are listed in Table 44.

Table 44 - Project tests and completions dates

Barrier	Placing of the last gate	Testing	General Testing	Completion
Lido Treporti	August 2014	January 2020	May 2020	31 December 2021
Lido S. Nicolò	January 2019	January 2020		
Malamocco	July 2017	December 2019		
Chioggia	N/A	August 2019		

Accessory systems, such as some compressor batteries, furnishings, elevators, various pipes and numerous hydraulic actuators were still to be done. The barriers were experimentally activated at the time, but the final tests have not been taken yet. The control room and the authorization procedure for the opening and closing of the mobile dams are also unfinished (Certifico, 2019). The next phase, after the testing of the last sluice gates, should be the completion of the final system, which will be followed by the last experimental management phase. Total expenditure on the project is estimated to amount to €7 billion (Il Post, 2019). The final estimated completion date is 31 December 2021 (Scotti, 2019).

5.8 Status of the Mo.S.E. Project During the 2019 Flood Event

At the time of the 2019 flooding event, the work on the Mo.S.E. barrier was 94% completed. However, the high tide phenomenon that flooded Venice on November 2019 urged the CNV to finish the works as soon as possible. The latest official schedule stated that by the end of 2018, the mobile barriers at all three inlets should be completed, while the construction of the technology systems should have started. Also, by the end of 2018, the management of the barrier with temporary systems should have been allowed, in line with the final testing of the barrier. The completion of the technology system works was scheduled by June 2020, allowing the management to update their systems and be fully operational. The handover was finally scheduled for the end of 2021 (Ministero dell Infrastrutture e dei Trasporti, 2020)

5.8.1 Why the Barrier Wasn't Lifted in 2019

This paragraph refers to the decision-making process that took place during the 12/11/2019 flood event. The following conclusions are drawn from two different interviews which can both be found in an extended version in Appendix N and Appendix O respectively.

In the specific case of 2019, when the high tide reached extreme levels (+187 cm), the high tide was forecasted at a maximum value of 150-160 cm (Scotti, 2019).

According to Giovanni Cecconi and to the Mayor of Chioggia, during the 2019 event the entire Lido mouth, the closest to Venice and therefore the most impactful, could have been closed. This would have mitigated the tide by roughly 35 cm and tested the mathematical model which considers the boundary condition and wind forcing under the circumstance of 2019 flooding. If the event is prolonged, then the whole lagoon reaches the water level, even if the flood comes from only one mouth. “If it is a very rapid peak, as in this case, there would have been this unexpected benefit” said Cecconi.

Alberto Scotti, on the other hand, considered it unacceptable to use the barrier before it was completed, even under urgent circumstance such as the November 2019 event. He claimed that, technically, the barrier could have been operated, but the system couldn’t have managed the high tide, given that the controlling systems weren’t ready. More specifically, to operate the barrier and raise it in 30 minutes, as the indicated by the scope of the project, 3 compressors are needed. At the time of the 2019 flooding even, only one compressor was installed. In such a case, it would have taken 5 hours for the barrier to rise completely. Although the high tide was forecasted a day before the event, the Mo.S.E. system, according to Alberto Scotti, should and must be operated only when the water reaches a certain level, around 80-90 cm. Even in the hypothetical case in which the barrier would have been operational, the barriers at the Lido and Chioggia inlets would have not have successfully mitigated the flooding due to the recent discovery of a technical problem caused by vibration in Malamocco. As he stated, the decision to not operate the barrier was not easy and he along with Attorney Fringo and engineer Ossola took all the responsibility for the decision. Operating the barrier, which had not been through the required testing phases yet, would have meant risking the flooding of the galleries where the technicians work. In addition, with only one compressor, sea water was likely to overcome the barrier from the top, resulting in the high flooding event anyway.

5.9 Conclusions and findings

The Mo.S.E. barrier is a part of the REA mega-project. After a long period of real-scale experiments, simulations and testing, the construction of the Mo.S.E. barrier finally began in 2003. The tenderer, CVN is contracted for both the design and the construction and the management of the barrier, by means of member companies and sub-tenders.

While the design of the barrier was carried out by one single company, the construction of the barrier was divided into four sub-projects, one for every barrier, carried out by different companies for most of the activities. The lack of coordination optimization, in the eyes of some of the companies who participated to the project, negatively influenced the project (Westerdorp, 2020). Project complexity is found to be at most in the external context which the project develops in. Uncertainty also plays a big role in this case, as the innovative nature of the project doesn’t allow for any comparable project worldwide.

Currently, the barrier is not finished and is estimated to be at its 95% of completion, but its delivery is schedules, at last, for the end of 2021. The project suffered many delays, some due to technical problems, some others due to organizational problems. However, the most relevant delay resulted from the corruption scandal in 2014 and its consequences, which blocked the process of the project for almost 5 years. Some also attribute the delay to poor managerial schedule planning at the very beginning of the project. As the completion date approaches, the company who will take care of the management of the barrier is still to be appointed.

The Mo.S.E. barrier construction activities, as well at the REA project activities, are all funded by Italy as the project develops. Hence, there is a strong dependency from governments and local authorities. The project was, and still is, also subject to environmental parties’ oppositions and criticism, some of which managed to influence the project process causing delay. Whether the barrier should have been lifted in 2019 to save Venice or not, still remains a big question mark.

Chapter 6: Conclusion

Luisa Caporalini, Bram Deuss, Gabriela Godlewski

The research carried out has made it possible to answer to the research questions posed in Chapter 1. These answers are elaborated in the first section of this chapter. In the second section, recommendations are given for future research.

6.1 Answers to Research Questions

Conducting research on the hydraulic characteristics of the Venice Lagoon and the statistics of the November 2019 flood event has made it possible to answer the following questions:

- What were the oceanographic and meteorological conditions that lead to the 12 November 2019 event?
- What was the return period for the 12 November 2019 event?
- What is the return period for the sea level of +110 cm at which the MO.S.E. is designed to close?
- What is the return period of the climate change scenarios?

The November 2019 flood was the result of an intricate coincidence of events occurring in the atmosphere and in the ocean at the same time. The water level data recorded at Punta della Salute on that day indicated an unusually high astronomical tide. At the same time, the generation of Bora and Scirocco winds intensified a low-pressure phenomenon present in the atmosphere, which caused the water level to rise rapidly. This rapid rise in water level, coinciding with an already-extreme atmospheric tide, resulted in the second-highest water level event in recent history in Venice.

The return period of the sea level of the November 2019 event was found through research of existing return period data. Comparing the water level of 187 cm available data, the range of return periods for the November 2019 event was determined to be 130 – 140 years. Using a similar method, the return period for the closure of the Mo.S.E. barrier was found to be 5 – 7 years.

Further literature research into available data pertaining to the anticipated rise in sea level in the 21st century was also conducted. This resulted in another estimation of the change in return periods as a result of the sea level rise. Two climate change scenarios were considered: one scenario assumed low emissions, and the second assumed high emissions. Under these scenarios, the return period range pertaining to the November 2019 event was reduced from 130 – 140 years to 50 – 100 years, while the Mo.S.E. barrier closure level was reduced from 5 – 7 years to 2 – 5 years. The new estimated ranges are very wide due to the uncertainty of the data pertaining to the rise in climate change, but both scenarios agree that the sea levels would rise and increase the frequency of extreme high water level events.

If the Mo.S.E. barrier were operational at the time of the 12 November 2019 event, the predetermined classification system would have assigned the incoming high water level event as Class 2. Therefore, the barrier would have had to begin raising at 65 cm and remain in the raised position for 7 hours in order to effectively prevent the 2019 flooding event.

As a result of the conducted research with a model concerning the impact of the November 2019 flood event, it has become possible to answer the following research questions.

- What were the flooded areas during the 2019 flood event and what were the water depths?
- What were the priced and unpriced damages as a result of the 2019 flood event?
- What have been flood prone areas in the past?
- If the barrier would have worked, how would it have affected the water levels and the damage?

The flooded areas in Venice during the 2019 flood event were determined to be 87.9% of the city center area, 79.0% of Lido, 74.1% of Pellestrina and 86.3% of the other islands within the lagoon.

The maximum water depths in the flooded areas during the November 2019 flood event come down to an average of 0.96 meter in the streets of the city center and an average of 0.91 meter in flooded buildings. This resulted in 5176 flooded buildings and 4114 flooded roads in the city center. The average maximum water depth in the streets of Lido was 1.06 meter and in flooded buildings it was 0.99 meter. As a result, 2287 buildings and 447 roads were flooded in Lido. The average maximum water depth in the streets of Pellestrina was 0.88 meter and in the flooded buildings it was 0.85 meter. This had the flooding 697 buildings and 156 roads in Pellestrina as a result. The average maximum water depth in the streets of the other islands was 1.16 meter and was 1.04 meter in the flooded buildings. 2192 buildings and 589 roads were flooded on these islands.

The total direct damage due to the November 2019 flood event is estimated at €870 million.

Also results have been achieved about the flooded cultural heritage as a result of the November 2019 flood event. In the city center 2090 buildings that are regarded as cultural heritage were flooded, 124 in Lido, 6 in Pellestrina and 201 on the other islands. The estimated direct damage to cultural heritage is €244 million.

Flood prone areas are situated throughout the whole lagoon. Some flooding starts at any water level higher than the reference level of Punta della Salute. Significant flooding of the city center occurs at a water level of approximately 0.8 meter.

If the Mo.S.E. barrier would have been in use during the 2019 flood event, the water level would have reached a maximum of 1.1 m in the lagoon. This would have resulted in the flooding of 1314 buildings and 1244 roads in the city center, 893 buildings and 197 roads in Lido, 126 buildings and 47 roads in Pellestrina and 897 buildings and 319 roads on the other islands. The total direct damage would be approximately €257 million. This is about €613 million less damage than has occurred without the Mo.S.E. barrier functioning.

The final part of this fact-finding report was developed to answer the following three main questions, further explored in the main text, by addressing several different sub-questions. The last part of the project's target is to answer the following research questions, by answering a series of related sub-questions, elaborated throughout chapter 5.

- What is the Mo.S.E. project and in what context can it be identified?
- Which typical Large Infrastructure Projects aspect most affected the Mo.S.E. project's process?
- Should the barrier have been operated during the emergency flooding event of 2019?

The mega-project REA, in which the Mo.S.E. barrier project can be contextualized, is a complex system of works targeting the safeguard of Venice. The project itself is managed in a very particular way, since funding are provided by the government on a progressive basis. The Mo.S.E. project was the main part of the REA mega-project and it consists of 4 mobile barriers, located at the three lagoon inlets, made up in total by 78 flap gates which are supposed to use Archimede's principle to safeguard Venice from exceptionally high tides. The Mo.S.E. project represents an engineering innovation incomparable to any other, as it promises to provide the safeguard of Venice being almost completely invisible. The project itself has a very high environmental impact, causing important opposition of many different Environmental Groups along with political entities such as the Ministry of the Environment. Although the opposition was strong, every effort to abort the project was eventually taken down by the supportive stakeholders.

As any other Large Infrastructure project, complexity couldn't be avoided in such a project. Surely, the project could and has been divided into four different projects, one for each barrier, to reduce its complexity, however this generated more interface problems eventually. The optimization of the project through coordination was ignored resulting in three different solutions (Westerdorp, 2020), with different characteristics and specifications. Plurality of links, contractors and stakeholders also played its role in the project process, as it increased the project's organizational complexity (Beccarini, 1996). The TOE framework applied to the Mo.S.E. project showed that external complexity was the most incisive complexity factor. As a matter of fact, the integration of a plurality of unforeseen risks and the progressively increasing timespan on which they spread should conclusively be evaluated as the most incident factor of the project. As an example, the risk of environmental opposition was most likely underestimated or poorly addressed and managed, resulting in delays in the early stages of the project, but also through its implementation. Corruption risk management was also not addressed seriously, as it did eventually have a grip on the entire project for years.

Conclusively, as the many delays suffered by the project led to a state of incompletion at the time of the 2019 flood event, although complete at its most, it is arguable that the barrier could and should have been operated at the time of the 2019 flood event. As technical engineer Alberto Scotti states in the interview he did for the local newspaper La Repubblica, the barriers were not in such a condition to upfront a high tide, given their state of completion. On the other hand, engineer Giovanni Cecconi, former director of the Control Room, suggested otherwise. Given the modularity of the barrier, it could have been possible and useful, according to him, to operate at least one of the three barriers during the high water event. Since the new schedule for the completion of the barrier released in 2019 stated that, by the end of 2018, the 3 barriers should have been ready to be managed and operated under temporary technical systems; either the official document has no relevance or the barrier should have been operated, to at least engage in the resistance towards the flooding.

6.2 Recommendations for Future Research

With the obtained return periods and corresponding water levels, it is possible to make predictions about future flood events in Venice. Research to the possible future impact and the amount of damage could be carried out for certain return periods, taking climate change into account. These future research projects will be able to utilize more recent data and produce more accurate results. More reliable estimates could also be made about the rate of sea level rise as a result of climate change due to more modern data and better technology.

By using the flooded amount of buildings and roads, the estimation of damage to buildings and roads in Venice has been done by using damage numbers from a report by Deltares (Deltares, 2015), which uses data from Dutch flooded buildings and Australian flooded roads. Damage to cultural heritage has been calculated with the same numbers. Research to damage numbers that correspond better to the buildings and roads in Venice could result in more accurate damage estimations. To properly determine the damage to cultural heritage, more specialized research into historical buildings and structures would be needed.

A literature investigation enabled to reconstruct the history and circumstances surrounding the Mo.S.E. barrier, its project management and most particularly its delay. As the Mo.S.E. project was influenced by corruption, additional research could focus on internal corruption prevention and management within large infrastructure works. Moreover, since it is known that climate change will result in the barrier closing more often and for longer than initially anticipated, research can be done to determine which modifications can be made to the design of the barrier so that the initial closure number of approximately 5 closures per year still effectively protects Venice.

Figures Index

Tables Index

Bibliography

Lane, F. C. (1973). *Venice: A Maritime Republic.* Baltimore: The John Hopkins University Press.

S. Munaretto, P. V. (2012). Flood Protection in Venice under Conditions of Sea-Level Rise: An Analysis of Institutional and Technical Measures. *Coastal Management, 40(4)*, pp. 355-380.

Dabala, C., & Campostrini, P. (2017). Una visione olistica, multidisciplinare e integrata per il Piano di monitoraggio della costruzione del MOSE. A holistic, multidisciplinary and integrated vision for the monitoring plan of the MOSE's construction. *Il controllo ambientale della costruzione del MOSE*, pp. 13-35.

Regione del Veneto. (2000). Piano per la prevenzione dell'inquinamento e il risanamento delle acque del bacino idrografico immediatamente sversante della laguna di Venezia. *Piano Direttore 2000*. Segreteria regionale all'ambiente.

CVN. (2014). *Non solo il MOSE*. Retrieved from MOSE: https://www.mosevenezia.eu/non-solo-mose/

Keane, J. (2013). Saving Venice: the MOSE Prject. *industry tap into news*.

CVN. (2019). *Non solo il Mose*. Retrieved from MOSE: https://www.mosevenezia.eu/non-solo-mose/

L. Carbognin, P. G. (1984). *An overview of the subsidence of Venice.* Venice, Italy: CNR.

D'Alpaos, L. (2010). *L'evoluzione morfologica della Laguna di Venezia attraverso la lettura di alcune mappe storiche e delle sue carte idrografiche.* Venice: Comune di Venezia.

Comune di Venezia. (2016). *Le acque alte eccezionali*. Retrieved from Città di Venezia: https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali

Suman, D., Guerzoni, S., & Molinaroli, E. (2005). Solutions for a complex coastal lagoon: integrated coastal management and Venice Lagoon. *Hydrobiologia, v. 550, pp. 1-18*, v. 550, pp. 1-18. Springer.

lonelyplanet.com. (2020, April 4). Retrieved from https://www.lonelyplanet.com/italy/venice/background/history/a/nar/1a3eef4f-9597-431d-b683-6b008190bbeb/360029

DW. (2019, December 6). Retrieved from https://www.dw.com/en/in-venice-the-floodwaters-recede-but-the-problems-pile-up/a-51557519

NBC News. (2019, November 24). Retrieved from https://www.nbcnews.com/news/world/venice-fears-exodus-residents-after-latest-flood-n1089566

The Sun. (2019, November 13). Retrieved from https://www.thesun.co.uk/news/7620018/venice-sink-flood/

NBC News. (2019, November 13). Retrieved from https://www.nbcnews.com/news/world/venice-floods-hit-second-highest-levels-ever-n1081076

BBC News. (2019, November 13). Retrieved from https://www.bbc.com/news/world-europe-50401308

The Art Newspaper. (2020, February 4). Retrieved from https://www.theartnewspaper.com/news/venice-counts-the-cost-of-worst-floods-since-1966

The New York Times. (2019, November 13). Retrieved from https://www.nytimes.com/2019/11/13/world/europe/venice-flood.html

Risk Management Monitor. (2019, December 4). Retrieved from http://www.riskmanagementmonitor.com/venice-sees-near-record-flooding/

Hyndman, D. &. (2009). *Natural Hazards and Disasters.* Brooks/Cole Cengage Learning.

The Verge. (2019, November 14). Retrieved from https://www.theverge.com/2019/11/14/20963878/venice-high-tide-climate-change-flood-barrier-sea-levels

The Guardian. (2019, November 14). Retrieved from https://www.theguardian.com/environment/2019/nov/13/waves-in-st-marks-square-as-venice-flooded-highest-tide-in-50-years

BBC News. (2019, November 13). Retrieved from https://www.bbc.com/news/world-europe-50409021

Travel and Leisure. (2019, December 26). Retrieved from https://www.travelandleisure.com/attractions/venice-flood-st-marks-square

Save Venice. (2020, March 3). Retrieved from https://www.savevenice.org/savevenice-and-the-italian-embassy-to-support-the-recovery-of-venice

wikiwand.com. (2020). Retrieved from https://www.wikiwand.com/en/Acqua_alta

The Guardian. (2015, June 15). Retrieved from https://www.theguardian.com/cities/2015/jun/16/inside-venice-bid-hold-back-tide-sea-level-rise

BBC News. (2003, July 17). Retrieved from http://news.bbc.co.uk/2/hi/europe/3069305.stm

CBS News. (2019, November 17). Retrieved from https://www.cbsnews.com/news/flooding-in-venice-venice-hit-by-record-third-exceptional-tide-in-one-week-2019-11-17/

encyclopedia.com. (2020, January 24). Retrieved from https://www.encyclopedia.com/environment/energy-government-and-defense-magazines/cultural-impacts-venice-peril-case-study

Forbes. (2019, November 18). Retrieved from https://www.forbes.com/sites/catherinesabino/2019/12/18/how-to-help-venice--and-what-to-know-about-visiting-after-the-floods/#1c7c115e20fc

EM-DAT. (2020, Februari 25). Retrieved from https://www.emdat.be/emdat_db/

Kundzewicz, Z. (2012). *Changes in Flood Risk in Europe.* IAHS Press.

wikipedia.org. (2020, March 6). Retrieved from https://en.wikipedia.org/wiki/1966_flood_of_the_Arno

The New York Times. (2016, November 7). Retrieved from https://www.nytimes.com/2016/11/08/world/europe/50-years-after-a-devastating-flood-fears-that-florence-remains-vulnerable.html

Arrighi, C. (2015). *Flood risk assessment in art cities: the exemplary case of Florence (Italy).*

BBC News. (2008, December 1). Retrieved from http://news.bbc.co.uk/2/hi/europe/7758204.stm

T. Neumann, K. A. (2013). *Comparing the "bathtub method" with the Mike 21 HD flow model for modelling storm surge inundation.* Kiel.

venipedia.org. (2020, April 9). Retrieved from http://www.venipedia.org/wiki/index.php?title=Merographic_Zero

CNR, ISMAR. (2019). *Venice: The exceptional high sea level event of 12/11/2019. Preliminary analysis of the data and discription of the phenomenon.*

openstreetmap.org. (2020, March). Retrieved from https://www.openstreetmap.org/

Piano Generale degli Interventi. (2020, March 3). Retrieved from MOSE: https://www.mosevenezia.eu/piano-generale-interventi/#mvbtab_56176e4781581_10

wikipedia.org. (2020, April 1). Retrieved from https://en.wikipedia.org/wiki/Acqua_alta

Judith Bosboom, M. J. (2015). *Coastal Dynamics I Lecture Notes CIE4305.* Delft: Delft University of Technology.

Live Science Staff. (2012, March 12). *Venice Menace: Famed City is Sinking & Tilting*. Retrieved from Live Science: https://www.livescience.com/19195-venice-sinking-slowly.html

Jenny M Brown, R. B. (2012). *Extracting sea level residual in tidally dominated estuarine environments.* Journal of Ocean Dynamics.

Ferrarin, C. (2019). *Venice: The exceptional high sea level event of 12/11/2019. Preliminary analysis of the data and description of the phenomenon.* Venice: Consiglio Nazionale delle Ricerche.

NOVA. (2002). *Sinking City of Venice.* Public Broadcasting Service.

Cavallaro, L. (2017). *Effect of Partial Use of Venice Flood Barriers.* Catania: Journal of Marine Science and Engineering.

Umgiesser, G. (2019, June). The impact of operating the mobile barriers in Venice (MOSE) under climate change. *Journal for Nature Conservation*. Venice, Italy: Institude of Marine Sciences.

Tomas, L. (2008, December 15). The tidal and wind induced hydrodynamics of the composite system Adriatic Sea/Lagoon of Vencie. *Journal of Continental Shelf Research*.

Cavallaro et al., L. (2017, December 11). Effect of partial use of Venice Flood Barriers. *Journal of Marine Science and Engineering*.

Fletcher, C., & Spencer, T. (2005). *Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge.* Cambridge: Cambridge University Press.

Lionello, P., Galati, M., & Elvini, E. (2010, April 10). Extreme storm surge and wind wave climate scenario simulations at the Venetian littoral. Lecce, Italy: Physics and Chemistry of the Earth.

Brambati, A., Carbognin, L., & Quaia, T. (2003). *The Lagooon of Venice: Geological setting, evolution and land subsidence.* Trieste, Italy: Journal of International Geoscience.

BBC News. (2019, November 15). Retrieved from https://www.bbc.com/news/world-europe-50430855

Deltares. (2015). *Updated and improved method for flood essessment: SSM2015.*

M. Reese, J. M. (2003). *Mikroskalige Evaluation der Risken in überflutungsgefährdeten Küstenniederungen.* Kiel, Germany.

Pirazzoli, P. A., Ullman, A., & Tomasin, A. (2007). *Extreme sea levels in two northern Mediterranean areas.* Meudon, France and Venice, Italy: Revue géographique des pays méditerranéens.

Mazzolin, L., & Micheletti, S. (2015). *Il sistema MOSE - Storia - Motivazioni e Lotte.* Venezia: Associazione AMBIENTEVENEZIA.

Seminara, G. (2008). Enrico Marchi e Venezia. *La salvaguardia di Venezia e la sua Laguna in ricordo di Enrico Marchi.* Venezia: Accademia Nazionale dei Lincei.

Filippi, Borioli, Cardinali, Esposito, Margiotta, Orrù, . . . Sonego. (2016). Legislatura 17 Atto di Sindacato Ispettivo n° 1-00584. Legislatura 17 Atto di Sindacato Ispettivo n° 1-00584: Senato della Repubblica.

Commissione VIA, C. (1998, December 9). Valutazione di impatto ambientale relativa al progetto: Interventi alle bocche lagunari per la regolazione dei flussi di marea. *Studio di impatto ambientale del progetto di massima*. Venice.

Kush, M. (2015, June). *The Statement Problem.* Retrieved from Quality Progress, The official pubblication of ASQ: http://asq.org/quality-progress/2015/06/one-good-idea/the-statement-problem.html

Paolucci, G. M. (2012). *Cerniere del Mose, cardini del sistema.* Padova.

Deheyn, D. D., & Shaffer, L. R. (2007, February 22). Saving Venice: Engineering and ecology in the Venice lagoon. *Technology in Society, Volume 29, Issue 2,*, pp. 205-213.

Ghetti, A., Marchi, E., Passino, R., Matildi, P., Pezzoli, G., Frassetto, R., & Angema, J. F. (1981). *Progetto di massima degli interventi alle bocche lagunari per la regolazione dei flussi di marea.*

Scotti, A. (1994). Progettazione delle opere di difesa dalle acque alte. *Quaderni Trimestrali*, p. 31.

Fantoni, V. (2017). Progetto MOSE a Venezia. *REALIZZAZIONE/infrastrutture*, pp. 15-16.

CVN. (2014). *I Cassoni*. Retrieved from MOSE: https://www.mosevenezia.eu/cassoni/

CVN. (2014). *Le Paratoie*. Retrieved from MOSE: https://www.mosevenezia.eu/paratoie/

Biraghi, A. (2014, December). L'oleodinamica nel progetto Mo.S.E. *Oleodinamica-pneumatica*, p. 23.

Paolucci, G. M. (2012). *Cerniere del Mose, cardini del sistema.* Padova.

Palolucci, G. M. (2012, February 28). *Le cerniere del MoSE, cardini del sistema.* Retrieved from MOSE: https://www.mosevenezia.eu/wp-content/uploads/2017/02/20120228_Relazione-sintesi-finale-Paolucci.pdf

CVN. (2017). *Cavalletta per installazione paratoie*. Retrieved from MOSE: https://www.mosevenezia.eu/my-product/cavalletta-per-paratoie-febbraio-2017/

CVN. (2015). *Come funziona il JACK-UP.* Retrieved from MOSE: https://www.mosevenezia.eu/wp-content/uploads/2015/04/come-funziona-il-JACK-UP-2.pdf

Cecconi, G. (2020, March 13). Interview. (L. Caporalini, Interviewer)

D'Alpaos, L., & Mel, R. (2017). SUI SOVRALZI DEI COLMI DI MAREA GENERATI DAL VENTO NELLA LAGUNA DI VENEZIA A CAUSA DELLA CHIUSURA DELLE PARATOIE MOBILI ALLE BOCCHE DI P. In L. D'Alpaos, *LA LAGUNA DI VENEZIA E LE NUOVE OPERE ALLE BOCCHE.* Venezia: Istituto Veneto di Scienze, Lettere e Arti.

Cecconi, G. (2013). La gestione operativa delle barriere del mose. *Quaderni Trimestrali*.

Rosselli. (2008). *Interventi per la salvaguardia di Venezia e il riequilibrio della laguna.* Retrieved from https://www.fig.net/resources/proceedings/2008/verona_am_2008_comm7/ppt/14_sept/4_2_rosselli_4.pdf

CVN. (2014). *Contol Room*. Retrieved from MOSE: https://www.mosevenezia.eu/control-room/

Luciano Mazzolin, S. M. (2015, January 17). *IL SISTEMA MOSE - STORIA – MOTIVAZIONI e LOTTE.* Retrieved from No Grandi Navi: http://www.nograndinavi.it/wordpress/wp-content/uploads/2015/03/2015-01-17-Scheda-NoMose-per-Tpp.pdf

Fregolent, L. (2014). *Studi Urbani e Regionali - Conflitti e Territorio.* Milan: Franco Angeli.

CVN. (2014). *Salvaguardia di Venezia - Cronologia Generale*. Retrieved from MOSE: https://www.mosevenezia.eu/cronologia/

Barlassina, G. (2014). Tutto sul MOSE. *Il Post*.

Lo Storto, C. (2015). *The MOSE project.* Megaproject.

High Council of Public Works. (1999). Problematiche relative alla tutela della laguna di Venezia . *Progetto di regolazione di flussi di mrea alle bocche di porto.* Venezia.

Standish, D. (2003). *Barriers to barriers: why environmental precaution has delayed mobile floodgates to protect Venice.* academia.edu.

Filippi, B. C. (2016). Legislatura 17 Atto di Sindacato Ispettivo n°1-00584. Legislatura 17 Atto di Sindacato Ispettivo n°1-00584: Senato della Repubblica.

Barocco. (2014, May 9). Mose, posizionato l'ultimo cassone al Lido di Venezia. *You Reporter, Corriere della Sera*.

Doni, N., & Signorelli, R. (1997). Le tecniche di Project Management applicate al progetto Venezia. *Quaderni Timestrali - Consorzio Venezia Nuova*.

Locatelli, G. &. (2017). *Corruption in public projects and mega-projects: There is an elephant in the room!* Internationa Journal of Project Managemet.

Il Post. (2014). L'inchiesta sul MOSE in 8 punti. *Il Post*.

Senato della Repubblica. (2019, November 19). 168a Seduta Pubblica. *Mozioni su iniziative a favore di Venezia alla luce di recenti eventi alluvionali*.

La Repubblica. (2019, November 15). Mose, lavori fermi da 5 anni. Lo studio: "Funzionerebbe". *La repubblica*.

Marchina, G. (2019). Inchiesta Mose, tutto quello che c'è da sapere (spiegato in tre minuti). *Open*.

Tijhuis, E. (2017, July 28). *Venice and the Mose project*. Retrieved from PlugIn Magazine: https://plugin-magazine.com/living/tech-venice-and-the-mose-project/

Tonacci. (2019, November 13). Venezia sommersa riscopre lo scandalo Mose, eterna incompiuta: Costato 5,5 miliardi e già obsoleto. *La Repubblica*.

Pecoraro, G. (2014). *Decreto gestione straordinaria.* Rome: Prefettura di Roma.

CVN. (n.d.). *Consorzio Venezia Nuova - Amminisrrazione Trasparente*. Retrieved from MOSE: https://www.mosevenezia.eu/consorzio-venezia-nuova/

Certifico. (2019, November 20). *https://www.certifico.com/costruzioni/370-news-costruzioni/9537-mo-s-e-modulo-sperimentale-elettromeccanico.* Retrieved from Certifico: https://www.certifico.com/costruzioni/370-news-costruzioni/9537-mo-s-e-modulo-sperimentale-elettromeccanico

Il Post. (2019, November 13). A che punto è il MOSE a Venezia? *Il Post*. Retrieved from Il Post: https://www.ilpost.it/2019/11/13/mose-venezia-lavori-conclusione/

Scotti, A. (2019, Novemeber 16). Il padre del Mose "Ho detto io: la diga resta giù Sarebbe stato come guidare una Ferrari senza freni". (F. Tonacci, Interviewer)

Il Post. (2019, November 13). La straordinaria acqua alta a Venezia. *Il Post*. Retrieved from Il Post: https://www.ilpost.it/2019/11/13/acqua-alta-venezia/

Ministero dell Infrastrutture e dei Trasporti. (2020, January 19). *Provveditorato Interregionale per le opere pubbliche.* Retrieved from provveditoratovenezia.mit.gov.it: http://provveditoratovenezia.mit.gov.it/files/cronoprogramma_lavori.pdf

Westerdorp, P. v. (2020). Stukton experience as CVN contractors. (B. J. Luisa Caporalini, Interviewer)

Beccarini, D. (1996). The concept of project complexity - a review. *Internationa Journal of Project Management, vol. 14, n. 4*, pp. 201-204.

Stravisi, F. (2011, July 23). *Caratteristiche meteorologiche e climatiche del Golfo di Trieste*.

Deputati, C. d. (1981). Il Progettone del 1981. Venice, Italy: Senato della Repubblica.

Umgiesser, G. (2020, April). The impact of operating the mobile barriers in Venice (MOSE) under climate change. *Journal for Nature Conservation, Volume 54*. Elsevier.

Cranley, E. (2019, December 23). *9 photos show flooding in Venice that has caused more than $1 billion in damages to the city's homes and historical sites*. Retrieved from Insider: https://www.insider.com/flooding-cost-1-billion-of-damage-to-venice-tourist-attractions-2019-12

BBC News. (2019, November 15). *Flooded Venice battles new tidal surge*. Retrieved from https://www.bbc.com/news/world-europe-50430855

UNESCO. (2020, March 29). *Venice and its lagoon*. Retrieved from whc.unesco.org: https://whc.unesco.org/en/list/394

Jacobson, A. (2019, December 4). *Venice Sees Near-Record Flooding*. Retrieved from Risk Management Monitor: http://www.riskmanagementmonitor.com/venice-sees-near-record-flooding/

Venipedia. (2019, December 5). *Demographics*. Retrieved from Venipedia: http://www.venipedia.org/wiki/index.php?title=Demographics

Colognesi, L. (2017, January 26). Lido di Venezia, a piedi dalle bocche di porte ai Murazzi, nel luoghi di Byron e Mann. *Globe Trotter Magazine*. Retrieved from Wikipedia: https://it.wikipedia.org/wiki/Murazzi_(diga)

CVN. (2020). *Piano Generale degli Inteverventi - Salvaguardia ambientale della Laguna di Venezia*. Retrieved from mosevenezia.eu: https://www.mosevenezia.eu/piano-generale-interventi/#mvbtab_56176e4781581_10

Regiove Veneto. (2020, February). *regione.veneto.it*. Retrieved from https://idt2.regione.veneto.it/idt/downloader/download#

Stella, G. A. (2005, June 14). Trentuno anni e costi quadruplicati, quando diremo basta alle mazzette? *Correire della Sera*.

Pietrobelli, G. (2020, January 14). Mose, la prova tecnica alla Bocca del Lido va a buon fine. La scommessa di De Micheli: “In caso di emergenza potremo alzare le paratie”. *Il fatto quotidiano*.

Pietrobelli, G. (2020, January 14). Mose, la prova tecnica alla Bocca del Lido va a buon fine. La scommessa di De Micheli: “In caso di emergenza potremo alzare le paratie”. *Il Fatto Quotidiano*.

Tonacci, F. (2019, November 13). *Venezia sommersa riscopre lo scandalo Mose, eterna incompiuta: Costato 5,5 miliardi e già obsoleto*. Retrieved from Repubblica: https://rep.repubblica.it/pwa/generale/2019/11/13/news/venezia_sommersa_riscopre_lo_scandalo_mose_eterna_incompiuta_costato_5_5_miliardi_e_gia_obsoleto_-241047632/

Certifico. (2019, November 20). *Mo.S.E. Electromechanical Experimental Module.* Retrieved from Certifico: https://www.certifico.com/costruzioni/370-news-costruzioni/9537-mo-s-e-modulo-sperimentale-elettromeccanico

UNESCO. (2020, March 29). *whc.unesco.org*. Retrieved from https://whc.unesco.org/en/list/394

de Bruijn, H., Jong, P., Korsten, A., & Van Zanten, W. (1996). *Grote Projecten: Besluitvorming & Management.* Alphen aan de Rijn: Samson HD Tjeenk Willink.

Bosh-Rekveldt, M., Jongkind, Y., Mooi, H., Bakker, H., & Verbraeck, A. (2010). Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *International Journal of Project Management*.

Appendix A - water depth raster for 1.87 m water level

In Figure 49, the water depth raster for a water level of 1.87 meter is shown. In this raster, each cell has an area of 25 m^2. The black cells have a water depth of 0 meter. As the water depth gets larger, the cells get a lighter shade of blue.

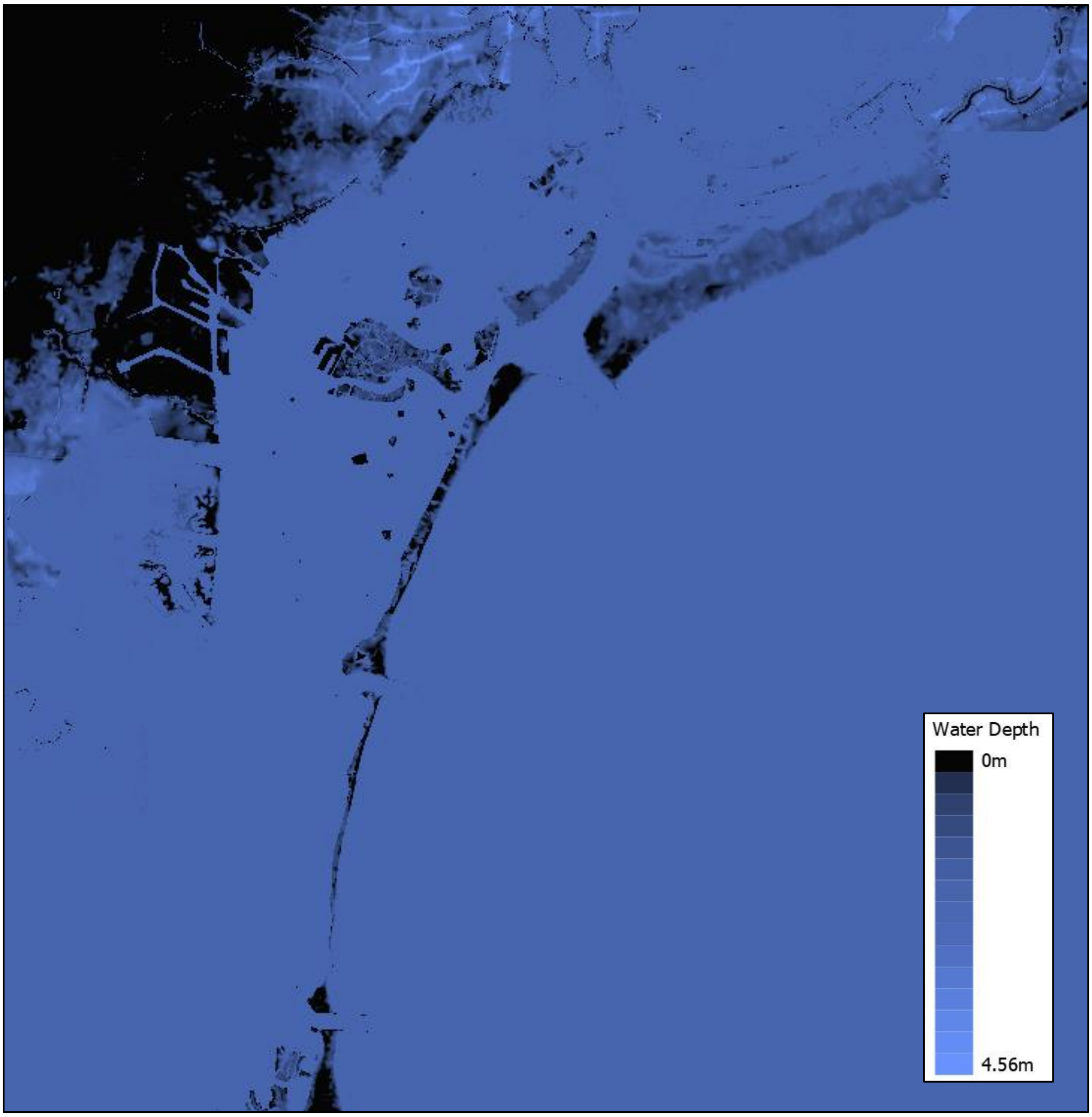
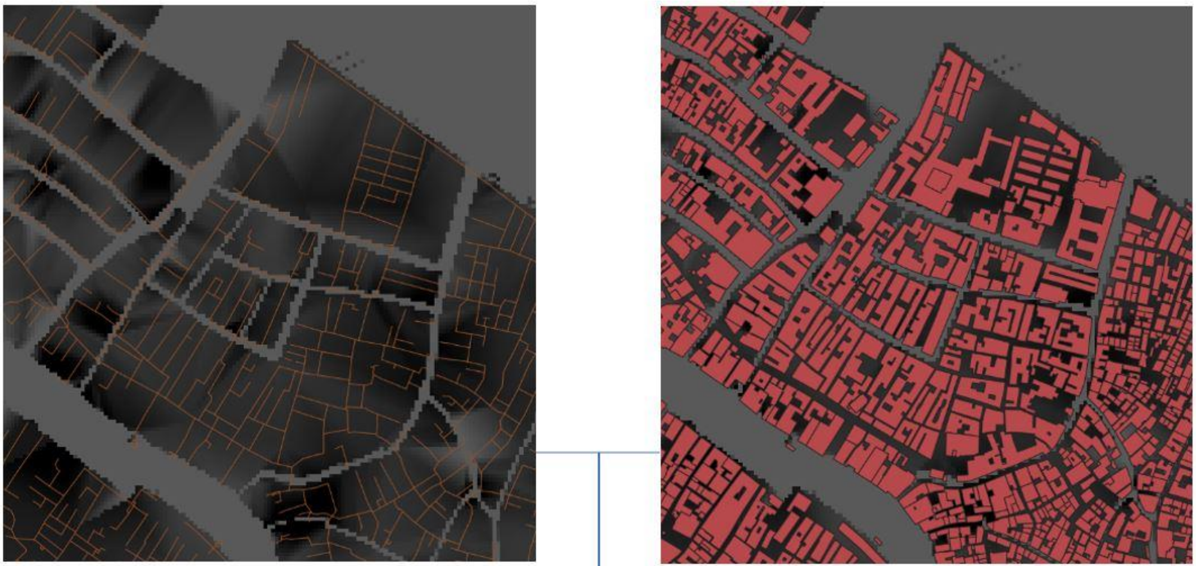


Figure 49 - Water depth raster for a water level of 1.87m

Appendix B -
Information flow from images to tables

Figure 50 shows how, by overlying the polygons and lines with the water depth raster, a table is obtained with information of each polygon and line, including the amount of cells within each polygon or line ('Area') and the water depth ('Mean Water Depth'). In this case an excerpt is used of a polygon table. Not all information in this polygon table is useable. For instance, in the first row no amenity is given and in the second row the building is 'yes'. By opening these tables as matrices in MALAB and comparing the water depth of each row with the threshold of flooding, information about the flooded polygons and lines can be added in a table.



Overlying polygons and lines with the raster and adding raster values to attribute tables of the polygons and lines

Building	Type	Amenity	Area	Mean Water Depth
'residential'	'Residential'	''	225	0.366021549
'yes'	'Police Station'	'police'	1125	0.233819

Comparing mean water depth of each row with threshold to obtain tables with flooded objects

Sub area	Number of flooded objects	Total area/length of flooded objects	Mean water depth of flooded objects
City center	x	x	x
Lido	x	x	x
Pellestrina	x	x	x
Other islands	x	x	x

Figure 50 - Process of creating tables with flooded objects

Appendix C – Flooded buildings data

Table 45 shows the flooded buildings as a percentage of the total amount of buildings per sub area for the November 2019 flood event.

	City center	Lido	Pellestrina	Other islands
Amount of flooded buildings	5176	2287	697	2192
Total amount of buildings	6315	3438	955	2745
Percentage flooded	82.0 %	66.5 %	73.0 %	79.9 %

Table 45 - Percentage of flooded buildings at water level of 1.87m

Table 46Table 45 shows the flooded roadsas a percentage of the total amount of roads per sub area for the November 2019 flood event.

	City center	Lido	Pellestrina	Other islands
Amount of flooded roads	4114	447	156	589
Total amount of roads	6281	654	273	807
Percentage flooded	65.5 %	68.3 %	57.1 %	73.0 %

Table 46 - Percentage of flooded roads at water level of 1.87m

Table 47 shows the flooded cultural heritage as a percentage of the total amount of buildings per sub area for the November 2019 flood event.

	City center	Lido	Pellestrina	Other islands
Amount of flooded heritage	2090	124	6	201
Total amount of buildings (not only heritage)	6315	3438	955	2745
Percentage flooded	33.1 %	3.6 %	0.6 %	7.3 %

Table 47 - Percentage of flooded cultural heritage at water level of 1.87m

Table 48 shows the flooded buildings as a percentage of the total amount of buildings per sub area for the situation when the Mo.S.E. barrier is closed.

	City center	Lido	Pellestrina	Other islands
Amount of flooded buildings	1314	893	126	897
Total amount of buildings	6315	3438	955	2745
Percentage flooded	20.8 %	26.0 %	13.2 %	32.7 %

Table 48 - Percentage of flooded buildings at water level of 1.1m

Table 49 shows the flooded roads as a percentage of the total amount of roads per sub area for the situation when the Mo.S.E. barrier is closed.

	City center	Lido	Pellestrina	Other islands
Amount of flooded roads	1244	197	47	319
Total amount of roads	6281	654	273	807
Percentage flooded	19.8 %	30.1 %	17.2 %	39.5 %

Table 49 - Percentage of flooded roads at water level of 1.1m

Appendix D - Flooding data related to different industry fields

The most important keywords available in the polygon matrices are the following. ‘Industry’, ’Church’, ‘Monastery’, ’Townhall’, ’University’, ‘School’, ‘Sports facility’, ‘Theatre’, ‘Police station’, ‘Fire station’, ‘Hospital’, ‘Garage’, ‘Parking’, and ‘Greenhouse’. These flooded buildings are shown in the tables below. It has to be noted that for convenience the monasteries are added to the churches and that the garages are added to the parkings.

Sub area	Amount of flooded industry	Total area of flooded industry	Mean water depth of flooded industry
City center	120	160000 m^2	0.80 m
Lido	35	23075 m^2	0.97 m
Pellestrina	12	10725 m^2	0.83 m
Other islands	131	137150 m^2	0.92 m

Sub area	Amount of flooded churches	Total area of flooded churches	Mean water depth of flooded churches
City center	107	100325 m^2	0.83 m
Lido	5	2700 m^2	0.85 m
Pellestrina	4	2575 m^2	0.74 m
Other islands	17	9375 m^2	1.07 m

Sub area	Amount of flooded townhalls	Total area of flooded townhalls	Mean water depth of flooded townhalls
City center	2	3025 m^2	1.04 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	1	475 m^2	0.84 m

Sub area	Amount of flooded universities	Total area of flooded universities	Mean water depth of flooded universities
City center	15	19900 m^2	0.87 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	1	4450 m^2	0.58 m

Sub area	Amount of flooded schools	Total area of flooded schools	Mean water depth of flooded schools
City center	14	38200 m^2	0.85 m
Lido	5	1050 m^2	1.05 m
Pellestrina	0	0 m^2	0.00 m
Other islands	4	4050 m^2	0.99 m

Sub area	Amount of flooded sports facilities	Total area of flooded sports facilities	Mean water depth of flooded sports facilities
City center	1	2600 m^2	1.08 m
Lido	0	0 m^2	0.00 m
Pellestrina	1	25 m^2	0.68 m
Other islands	2	450 m^2	0.66 m

Sub area	Amount of flooded theatres	Total area of flooded theatres	Mean water depth of flooded theatres
City center	4	2900 m^2	0.74 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded police stations	Total area of flooded police stations	Mean water depth of flooded police stations
City center	4	5900 m^2	0.94 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded fire stations	Total area of flooded fire stations	Mean water depth of flooded fire stations
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded hospitals	Total area of flooded hospitals	Mean water depth of flooded hospitals
City center	1	6500 m^2	0.69 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded parking	Total area of flooded parkings	Mean water depth of flooded parkings
City center	1	2425 m^2	0.43 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded greenhouses	Total area of flooded greenhouses	Mean water depth of flooded greenhouses
City center	1	525 m^2	0.92 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	62	24100 m^2	1.02 m

The most important keywords available in the line matrices are the following. ‘Steps’, ‘Motorway’, ’Highway’, ’Pedestrian’, ’Footway’, ‘Footpath’, ‘Cycleway’, ‘residential road’, and ‘living street’. The information that is obtained in this way is added for all sub areas into one table per keyword. ‘Steps’ refers to bridges. As stated before, most bridges are unjustifiably flooded according to the bathtub model. Therefore, bridges are not taken into account. It has to be noted that the highways are added to the motorways, that the living streets are added to the residential roads and that the footways and cycleways are all added to the footpaths.

Sub area	Amount of flooded motorways	Total length of flooded motorways	Mean water depth of flooded motorways
City center	13	1020 m	1.41 m
Lido	0	0 m	0.00 m
Pellestrina	0	0 m	0.00 m
Other islands	0	0 m	0.00 m

Sub area	Amount of flooded footpaths	Total length of flooded footpaths	Mean water depth of flooded footpaths
City center	4075	147975 m	0.97 m
Lido	119	17420 m	1.21 m
Pellestrina	90	9220 m	0.92 m
Other islands	497	37755 m	1.18 m

Sub area	Amount of flooded residential roads	Total length of flooded residential roads	Mean water depth of flooded residential roads
City center	25	2345 m	0.89 m
Lido	239	29965 m	1.03 m
Pellestrina	55	10305 m	0.80 m
Other islands	41	8450 m	1.01 m

Appendix E –
Flooded Cultural Heritage data

Information about the flooded cultural heritage due to the November 2019 flood event is shown in the tables below for each building type.

Sub area	Amount of flooded industry	Total area of flooded industry	Mean water depth of flooded industry
City center	64	114700 m^2	0.79 m
Lido	3	10125 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	6	7550 m^2	0.77 m

Sub area	Amount of flooded churches	Total area of flooded churches	Mean water depth of flooded churches
City center	61	44650 m^2	0.86 m
Lido	2	250 m^2	0.37 m
Pellestrina	1	1025 m^2	0.69 m
Other islands	5	3925 m^2	0.91 m

Sub area	Amount of flooded townhalls	Total area of flooded townhalls	Mean water depth of flooded townhalls
City center	2	2800 m^2	1.04 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	1	400 m^2	0.84 m

Sub area	Amount of flooded universities	Total area of flooded universities	Mean water depth of flooded universities
City center	4	6050 m^2	0.76 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	1	4375 m^2	0.56 m

Sub area	Amount of flooded schools	Total area of flooded schools	Mean water depth of floodes schools
City center	3	5900 m^2	0.71 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	2	1075 m^2	0.93 m

Sub area	Amount of flooded sports facilities	Total area of flooded sports facilities	Mean water depth of flooded sports facilities
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded theatres	Total area of flooded theatres	Mean water depth of flooded theatres
City center	2	1450 m^2	0.89 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded police stations	Total area of flooded police stations	Mean water depth of flooded police stations
City center	3	1425 m^2	0.81 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded fire stations	Total area of flooded fire stations	Mean water depth of flooded fire station
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded hospitals	Total area of flooded hospitals	Mean water depth of flooded hospitals
City center	1	6350 m^2	0.69 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded parkings	Total area of flooded parkings	Mean water depth of flooded parkings
City center	1	75 m^2	0.57 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded greenhouses	Total area of flooded greenhouses	Mean water depth of flooded greenhouses
City center	1	525 m^2	0.92 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Appendix F –
Damage to Cultural Heritage

The damage to cultural heritage due to the November 2019 flood event is shown in the tables below for each building type.

	City center	Lido	Pellestrina	Other islands
Damage to houses	€ 89,761,502	€ 5,483,377	€ 230,394	€ 8,570,657

	City Center	Lido	Pellestrina	Other Islands
Damage to industry	€ 101,741,741	€ 8,515,273	€ -	€ 6,686,066

	City center	Lido	Pellestrina	Other islands
Damage to health services	€ 6,643,497	€ -	€ -	€ -

	City center	Lido	Pellestrina	Other islands
Damage to education	€ 6,289,166	€ -	€ -	€ 2,868,281

	City center	Lido	Pellestrina	Other islands
Damages to sports facilities	€ -	€ -	€ -	€ -

	City center	Lido	Pellestrina	Other islands
Damage to churches	€ 6,466,000	€ 212,000	€ 106,000	€ 530,000

Appendix G -
Dry and flooded areas

The dry and flooded areas at a water depth of 1.87 meter are clarified here in figures for the city center, Lido, Pellestrina and the northern other islands in the lagoon (the southern other islands are already shown in the other figures). Just as in section 3.4, the black areas show areas that are still dry.

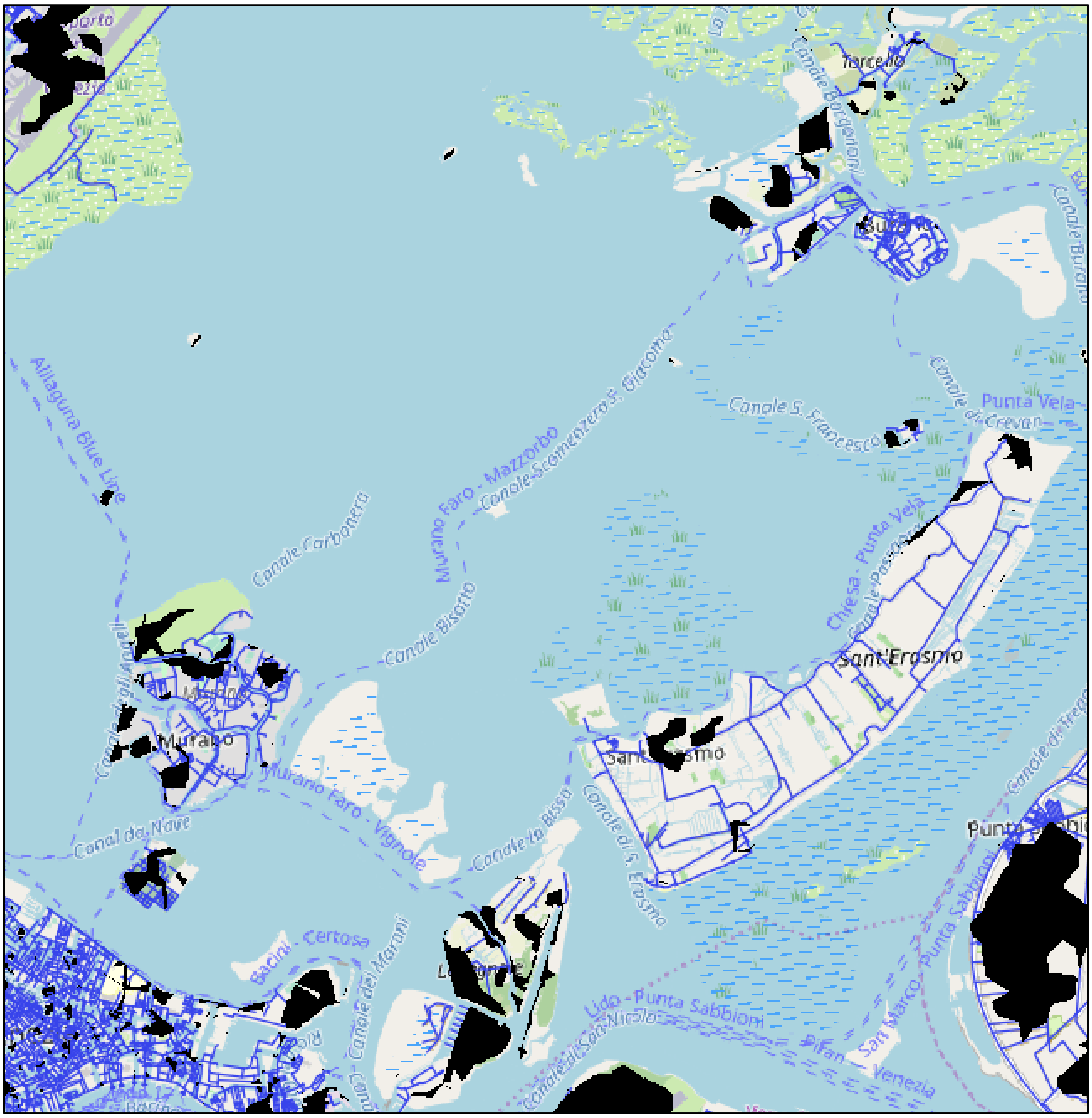


Figure 51 - Flooded and dry areas according to the model of the other islands in the norther part of the lagoon at water level of 1.87m

Figure 52 - Flooded and dry areas according to the model of the city center at water level of 1.87m

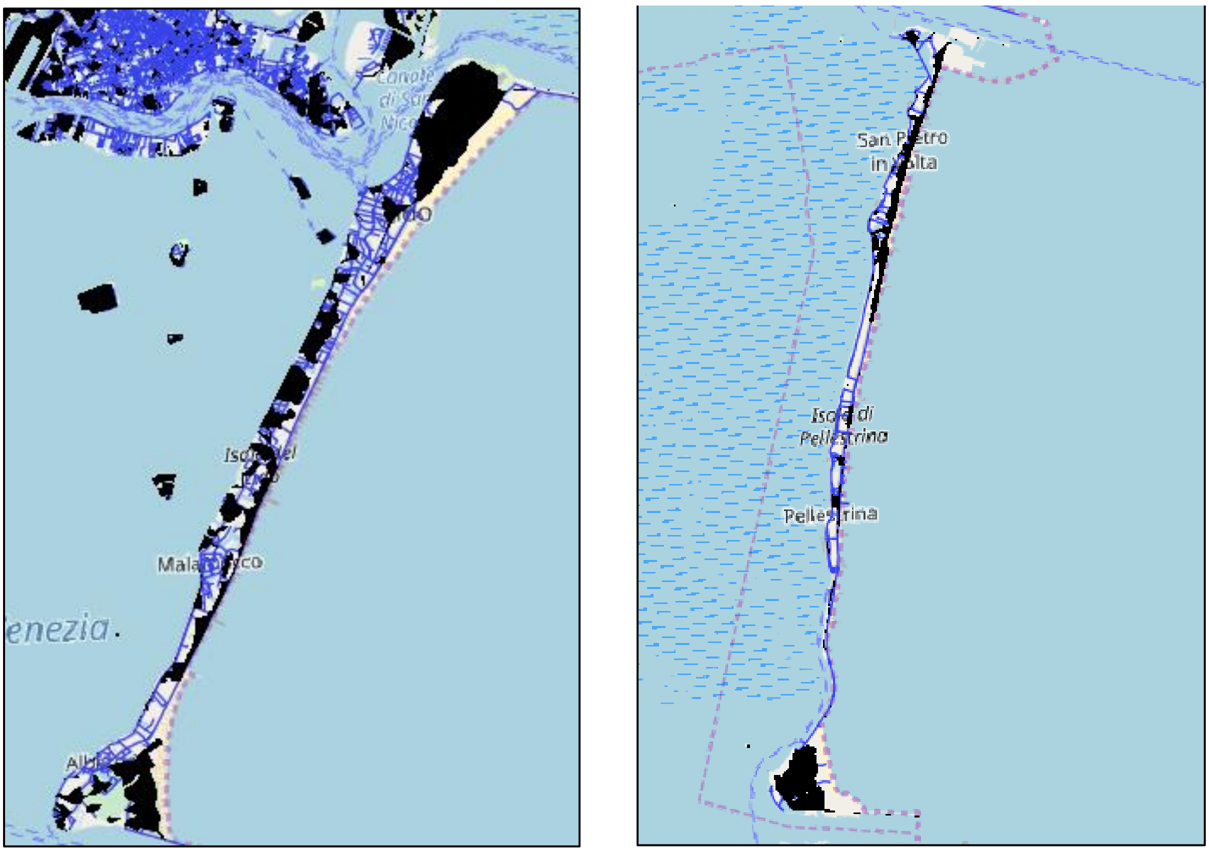


Figure 53 – Left: Flooded and dry areas according to the model of Lido at water level of 1.87m. Right: Flooded and dry areas according to the model of Pellestrina at water level of 1.87m

Appendix H - Probability density functions plotted against water level

Just as the cumulative distribution function, the probability density function can be plotted against the water level. See the figures below.

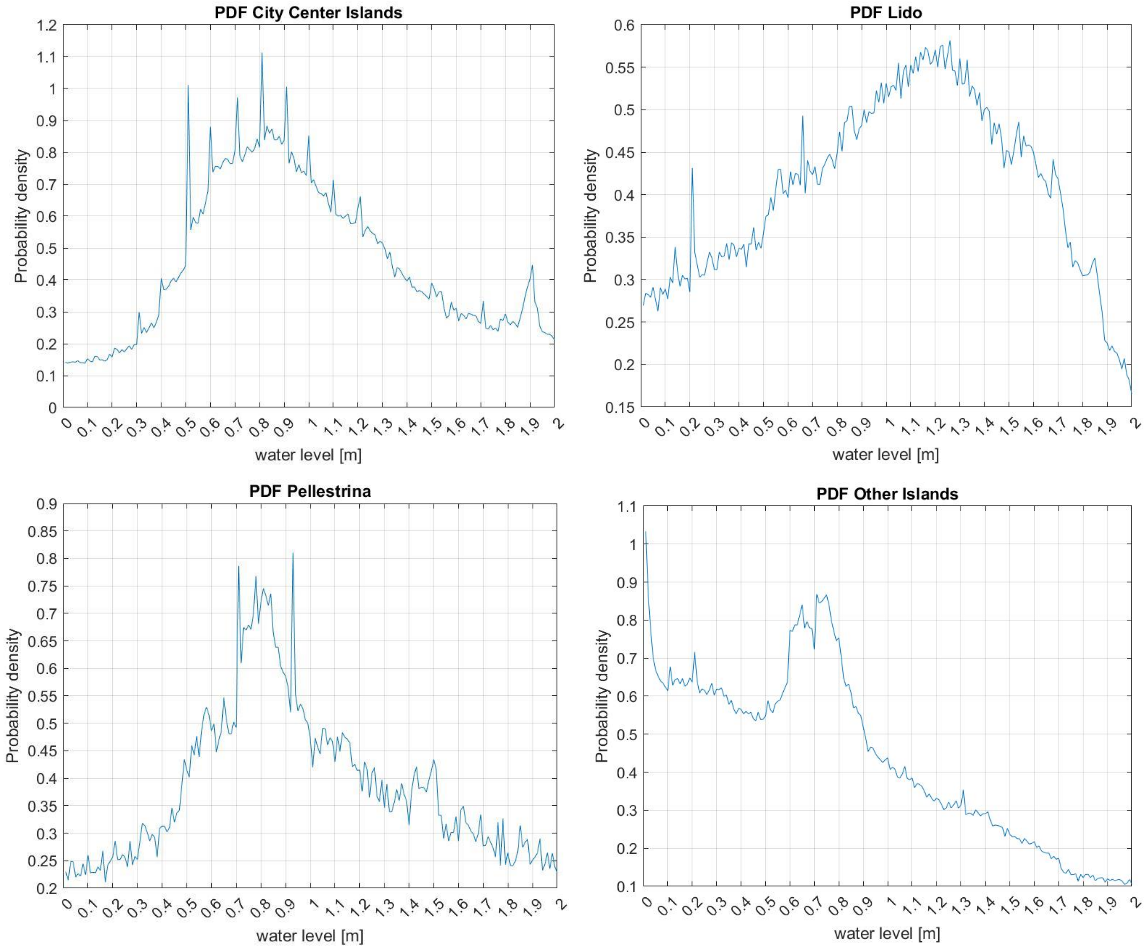


Figure 54 – Probability density functions over the water level for respectively the city center, Lido, Pellestrina and the other islands

Also, these probability density functions can be plotted against the percentage of the flooded area instead of the water level. See figures on the next page.

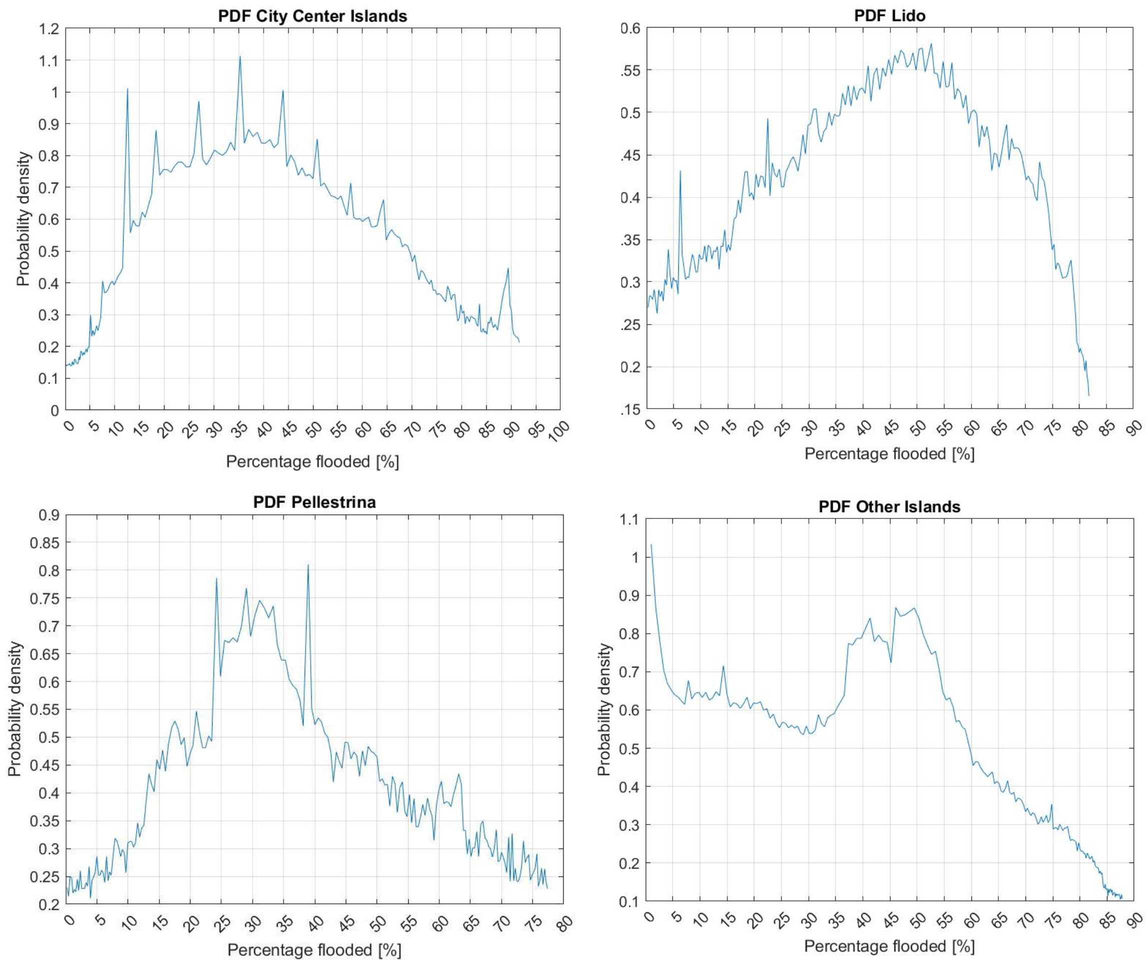


Figure 55 – Probability density functions over the percentage of flooded area for respectively the city center, Lido, Pellestrina and the other islands

It can be noticed that there are some large peaks; for instance in the city center at a water level of 0.5 meter and a flooded percentage of 12%. These peaks can be explained by large gradients in the flooded percentage, due to a large number of cells that suddenly get flooded in one step (or a few succeeding steps) of increasing water level. For instance, at the same water level at the peak in the PDF of the city center at 0.5 meter, a step can be seen at the same water depth in the CDF (Figure 31).

Appendix I - Flooded buildings data with closed barrier

Information about the flooded buildings and roads is shown in the tables below for each building type regarding the highest water level when the Mo.S.E. barrier is closed (1.1 meter).

Sub area	Amount of flooded industry	Total area of flooded industry	Mean water depth of flooded industry
City center	18	13125 m^2	0.61 m
Lido	15	10150 m^2	0.61 m
Pellestrina	2	350 m^2	0.34 m
Other ilslands	35	50725 m^2	0.83 m

Sub area	Amount of flooded churches	Total area of flooded churches	Mean water depth of flooded churches
City center	15	10825 m^2	0.50 m
Lido	1	875 m^2	0.40 m
Pellestrina	0	0 m^2	0.00 m
Other ilslands	10	3975 m^2	0.59 m

Sub area	Amount of flooded townhalls	Total area of flooded townhalls	Mean water depth of flooded townhalls
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other ilslands	0	0 m^2	0.00 m

Sub area	Amount of flooded universities	Total area of flooded universities	Mean water depth of flooded universities
City center	6	3725 m^2	0.63 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other ilslands	0	0 m^2	0.00 m

Sub area	Amount of flooded schools	Total area of flooded schools	Mean water depth of flooded schools
City center	3	3050 m^2	0.76 m
Lido	4	400 m^2	0.48 m
Pellestrina	0	0 m^2	0.00 m
Other ilslands	1	2200 m^2	0.73 m

Sub area	Amount of flooded sports facilities	Total area of flooded sports facilities	Mean water depth of flooded sports facilities
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded theatres	Total area of flooded theatres	Mean water depth of flooded theatres
City center	1	1450 m^2	0.39 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded police stations	Total area of flooded police stations	Mean water depth of flooded police stations
City center	4	5900 m^2	0.94 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded fire stations	Total area of flooded fire stations	Mean water depth of flooded fire stations
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded hospitals	Total area of flooded hospitals	Mean water depth of flooded hospitals
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded parking lots	Total area of flooded parkings lots	Mean water depth of flooded parking lots
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	0	0 m^2	0.00 m

Sub area	Amount of flooded greenhouses	Total area of flooded greenhouses	Mean water depth of flooded greenhouses
City center	0	0 m^2	0.00 m
Lido	0	0 m^2	0.00 m
Pellestrina	0	0 m^2	0.00 m
Other islands	23	12050 m^2	0.52 m

Sub area	Amount of flooded motorways	Total length of flooded motorways	Mean water depth of flooded motorways
City center	10	875 m	0.88 m
Lido	0	0 m	0.00 m
Pellestrina	0	0 m	0.00 m
Other islands	0	0 m	0.00 m

Sub area	Amount of flooded footpaths	Total length of flooded footpaths	Mean water depth of flooded footpaths
City center	1222	40240 m	0.74 m
Lido	70	7110 m	0.80 m
Pellestrina	30	3640 m	0.68 m
Other islands	284	21160 m	0.80 m

Sub area	Amount of flooded residential roads	Total length of flooded residential roads	Mean water depth of flooded residential roads
City center	12	1050 m	0.65 m
Lido	104	11220 m	0.77 m
Pellestrina	14	1730 m	0.65 m
Other islands	15	2790 m	0.62 m

Appendix J - Damage to building and roads data

The damage to buildings and roads is shown in the tables below for each building type regarding the highest water level when the Mo.S.E. barrier is closed (1.1 meter).

	City center	Lido	Pellestrina	Other islands
Damage to houses	€ 58,381,840	€ 40,226,792	€ 5,713,771	€ 38,153,246

	City Center	Lido	Pellestrina	Other Islands
Damage to industry	€ 41,642,838	€ 16,008,713	€ 4,877,885	€ 26,954,518

	City center	Lido	Pellestrina	Other islands
Damage to health services	€ -	€ -	€ -	€ -

	City_Center	Lido	Pellestrina	Other_Islands
Damage to education	€ 3,565,615	€ 210,516	€ -	€ 1,157,838

	City center	Lido	Pellestrina	Other islands
Damages to sports facilities	€ -	€ -	€ -	€ -

	City center	Lido	Pellestrina	Other islands
Damage to churches	€ 1,590,000	€ 106,000	€ -	€ 1,060,000

	City center	Lido	Pellestrina	Other islands
Total damage to roads	€ 8,248,848	€ 3,083,867	€ 927,949	€ 4,216,100
Total cleaning costs roads	€ 443,535	€ 291,481	€ 70,034	€ 263,763

Appendix K -
General plan of interventions for the safeguard of Venice lagoon

The following pictures shows a map of all the works planned and implemented by the CVN in respects of the general work of intervention stipulated for the safeguard of Venice. The works are quantified in terms of completion in 2019.

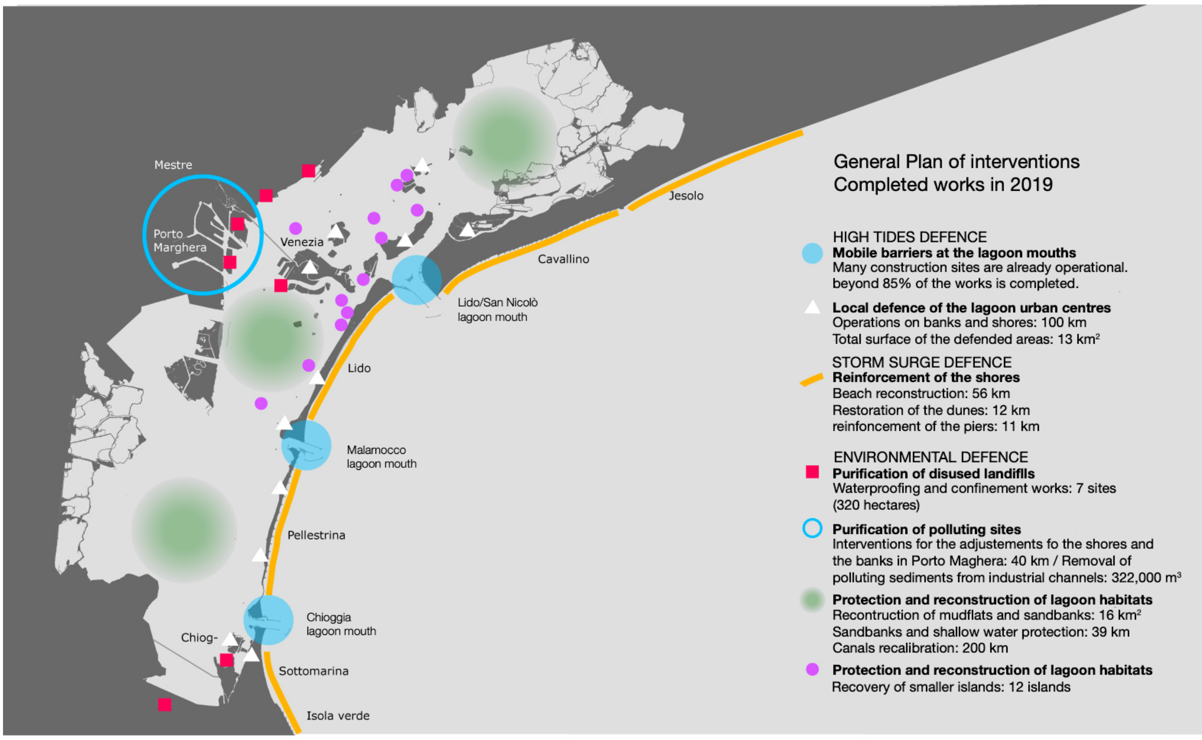


Figure 56 - Map of interventions categorized in respect to scope with relative completion state in 2019 (CVN, 2019)

Appendix L - Complexity analysis through TOE framework test

	Element	Explanation (with an indication of scale between brackets)	Contribution in the Mo.S.E. project
Technical	**High number of project goals**	Think of "strategic" project goals (single – many)	4
	Non-alignment of project goals	Only if more than one strategic goal is present: amount of non-alignment (completely aligned – completely unaligned)	3
	Unclarity of project goals	Unclarity of project goal(s) amongst team members (totally clear – totally unclear)	3
	Uncertainties in scope	Presence of uncertainties in agreed scope of work (no uncertainties – lots of uncertainties)	4
	Strict quality requirements	Think of quality requirements for project deliverables (normal – extraordinary high)	5
	Project duration	How long is the planned duration, compared to your reference (short – very long)	5
	Size in CAPEX	Capital expenditure: total investment for the realization of the project (small for the company – very large for the company)	5
	Number of locations	The number of different sites / locations involved in the project, including contractor's locations (one – multiple)	2
	Newness of technology (worldwide)	wide) Does the project make use of new technology e.g. nonproven technology (technology which is new in the world for this application (no new technology – highly innovative)	5
	Lack of experience with technology	Do the involved parties have experience with the technology used in the project (lot of experience – no experience)	5
	High number of tasks	Does the project have a lot of tasks, count for example work packages or subprojects (single – many)	3
	High variety of tasks	Does the project have lots of different types of tasks? (very similar tasks – very different tasks)	3
	Dependencies between tasks	What is the number and nature of dependencies between the different tasks? (small – many & pooled)	4
	Uncertainty in methods	Are there lots of uncertainties in technological methods to be expected (no - yes)	5
	Involvement of diff. tech. disciplines	What is the level of multi-disciplinarity? (single – very multidisciplinary)	3
	Conflicting norms and standards	Are there conflicting design standards and country specific norms included in the project (few – many)	3
	Technical risks	Do you consider the project being high risk (number, probability and/or impact) in terms of technical risks (no risk –very high risk)	5
The potential contribution to the project's complexity is assessed using the following scale: None (1) – little (2) – some (3) – substantial (4) – very much (5)			

	Element	Explanation (with an indication of scale between brackets)	Contribution in the Mo.S.E. project
Organizational	**High project schedule drive**	How high was the pressure on the project schedule? (not at all – should be finished yesterday)	5
	Lack of resource & skills availability	Are there any problems in the availability of the resources (materials, personnel) and skills required for the project (all available – major problems in availability)	2
	Lack of experience with parties involved	Did you work before with the parties involved in the project, like JV partner, contractor, supplier (many times – no experience)	2
	Lack of HSSE awareness	Are the involved parties aware of the importance of Health, Safety, Security and Environment (HSSE) issues? (fully aware – not aware at all)	2
	Interfaces between diff. disciplines	Are there many interfaces between the different disciplines involved (like mechanical, electrical, chemical, civil, finance, legal, communication, accounting, etc) that could lead to interface problems? (few interfaces – many interfaces)	4
	Number of financial sources	How many different financial sources does the project have, like own investment, bank investment, subsidies, JVpartners, customer(s)? (single source – multiple sources)	1
	Number of contracts	How many different contracts are involved in the project, think of contracts with the customer, the contractors, suppliers, etc (single contract – multiple contracts)	4
	Type of contract	Are these all different or all the same and Is the chosen contract type adequate for the project? (all the same / OK, all different / not adequate)	2
	Number of different nationalities	What is the number of different nationalities involved in the project? (single – multiple)	3
	Number of different languages	How many different languages are used in the project communication? (single – multiple)	2
	Presence of JV partner	Do you cooperate with a JV (joint venture) partner in the project? (no – yes)	5
	Involvement of different time zones	Are there different time zones involved in the project, as a result of which for example planning of joint meetings is more difficult? (single time zone or limited impact – multiple time zones, major impact)	1
	Size of project team	How many persons are within the project team (few (1-5) - many (>200))	4
	Incompatibility between different PM methods / tools	Do you expect compatibility issues regarding project management methodology or project management tools between involved parties? (no compatibility issues expected – major issues expected)	2
	Lack of trust in project team	Do you trust the members of the project team (completely – not at all)	3
	Lack of trust in contractor	Do you trust the contractor(s) involved (completely – not at all)	4
	Organizational risks	Do you consider the project being high risk (number, probability and/or impact) in terms of organizational risks (no risk –very high risk)	4
The potential contribution to the project's complexity is assessed using the following scale: None (1) – little (2) – some (3) – substantial (4) – very much (5)			

	Element	Explanation (with an indication of scale between brackets)	Contribution in the Mo.S.E. project
External	**Number of external stakeholders**	How many external (e.g. outside the project team) stakeholders are involved in the project (like NGO's, (local) governments, different departments, suppliers, local residents, etc); those parties that can influence or are influenced by the project? (few – many)	5
	Variety of external stakeholders' perspectives	To what extent do the perspectives of the different stakeholders differ? (not so much differences – completely different)	4
	Dependencies on external stakeholders	What are the dependencies on the external stakeholders (no dependencies – many and very crucial dependencies)	4
	Political influence	To what extent does the political situation influence the project (no political influence – severe political influence)	5
	Lack of company internal support	Is there enough company internal management support for the project? (enough support – not supported)	1
	Required local content	To what extent are local parties obliged to participate in the project in order to have permission to execute the project (no local parties required – large part of the project should be executed by local parties)	5
	Interference with existing site	Do you expect interference between the current site or the current use of the site and the (foreseen) project location? (no interference, Greenfield – lot of interference, Brownfield)	5
	Remoteness of location	How remote is the project location located, think of reachability, availability of infrastructure and other facilities (easily reachable – very remote)	1
	Lack of experience in the country	Do the involved parties already have worked in the country before? (yes, several times – no experience at all)	1
	Company internal strategic pressure	Is there internal strategic pressure from within the company/organization, for example from the business or competitive departments? (no internal pressure – high internal pressure)	2
	Instability of project environment	What is the stability of the project environment, think of exchange rates, raw material prices, economic situation (very stable environment – very instable environment)	3
	Level of competition	What is the level of completion related to current market conditions (no competition – very strong competition)	3
	External risks	Do you consider the project being high risk (number, probability and/or impact) in terms of external risks (no risk –very high risk)	4
The potential contribution to the project's complexity is assessed using the following scale: None (1) – little (2) – some (3) – substantial (4) – very much (5)			

Appendix M - Interview with Peter van Westendorp

Interview with Peter van Westendorp, Director of Operations at Strukton immersion projects bv

Interviews: Luisa Caporalini, S.N. Jonkman, conducted on 14/04/2020

what was the general scope/objective you've been given to complete the work? Our Scope during this project (Chioggia Inlet) was the Float up, transport and immersion of the two shoulder and 6 gate caissons. The placing tolerance was +/- 10 mm dX, dY and dZ

The contract included the design of the immersion pontoon with al it systems and complete outfitting of the pontoon. Within this scope the main contractor had designed and installed the ballast system. After the installation we assisted with the diving works for the grouting under the caissons

How was the work structured among your companies and the other companies working in parallel to you? We had a contract as a subcontractor for the Main contractor Clodia. At the time that we signed our contract the construction of the Caissons was almost completed. The contractors for the Ballastsystem, jacking systems and grouting systems all had subcontracts with the main contractor Clodia.

What does the maintenance of the caissons / tunnels consist of and what are the costs and times for the maintenance of these? This subject is unknown for us since we only did the installation of the caissons, all the remaining works regarding the installation of the gates and the operational systems took place long after we have completed our works.

Do you have any views on the organization of the MO.S.E. project (in which various construction activities were split up over various contractors and organizations)? The Italian way of organising projects differ from what we are used to. For instance the budget for the project was not available in full at the start of the project, the contractors had to submit budget request to the consortium and were given the budget if it was available. This resulted in a situation that the main contractors were not able to proceed with the project in a most optimum way. For example the caissons were almost completed at the time we as immersion contractor came on board. The decisions and therewith designs were in some cases not the best solution for the project.

Furthermore were the three inlets seen as three separate projects and was there no coordination in optimizing the construction and or immersion methods resulting in three different solutions

If you were given the opportunity to do this work again, what would you like to change and what would you ask the MO.S.E. project coordinators to improve in relations to the contractors and subcontractors?

Yes we would directly do this contract again, our relation with the main contractor Clodia has been very good and we work with them in a way that was best for project.

The main thing I would change is the fact that the three contractors did not coordinate the construction/immersion methods, by doing that I am convinced that a much shorter schedule would be realized although the budget situation is a crtitcal issue in the whole process and if that can not be changed your are forced to work as it are separate construction phases with its own schedules

Appendix N –
Interview with Giovanni Cecconi

Interview with Giovanni Cecconi, former director of the Control Room

Interviewers: Luisa Caporalini, Alessandro Antonini, conducted on 13/03/2020

How would you classify and describe the project?
The defense system can be classified as hybrid because it is based on local defenses, which can be raised compared to the reception zero of Punta della Salute. The reception zero is the "medium sea" measured in 1875, which nowadays is 33 cm below the average sea of the last 5 years. The zero of the aforementioned tide gauge was calculated by measuring the levels in 10 years, between 1970 and 1980, and deriving the average between the maximum and minimum obtained. By repeating the sea level over time, it was possible to obtain a curve of the growth of the sea level of Venice with respect to the ground. From it we can see that the sea level has grown about 35 m above zero in 120-140 years. The lowering of Venice, however, depends on the term of comparison with which it is measured, because the various movements of the soil in Venice depend on many factors: in general on a general subsidence due to the compaction of the Quaternary, which is found in around 700-800 m of deposits; then there is a subduction of the Apennine crust of the Alps below that of Dinarica, that is, the one that created the Apennines, which may have contributed to the lowering of the city. Generally the historical values are based on secular and by comparison with Trieste, imagining that Trieste was stable and therefore independent of the glacial hypostats, that is, by the fact that the caps discharging, gave rise to an increase in the rind of the northern regions and a lowering of regions to our latitudes. If this is true, then Trieste should also be affected. The famous graph that shows the anthropic subsidence of Venice compared to Trieste, in which the difference between the two cities is related to the extraction of water from the subsoil between 1930 and 1970, particularly in the last 20 years of the said period, and the relative pressurization effect that the extraction exerted by 12-15 cm of value in the above mentioned extraction period. Since then, the drainage of water from deep wells no longer occurs, therefore the subsidence effect is also blocked. However, there is still a movement of the soil, which is currently measured with INSAR techniques, which has revealed a subsidence in the historic city, slightly larger than 4-5 cm per century. This measurement could only concern the fact that construction works have been made, the ground has been vibrated, cruise ships pass which can create vibrations of the sands, therefore producing not so much the consolidation of the clay as the compaction of the sands, so there are greater failures than estimated. It must also be said that the INSAR reflectors are on the built ground and therefore on ground that can be subject to overloads and vibrations. Another hypothesis is that the flooding of Venice with these periodic submersions could also be a mechanism of pulsating overload of the sands and therefore of compaction. These are all of the scientific questions that you may want to browse, the main thing is the sea level that grows, for the rest the other things are not very relevant.

What are the preventive and corrective measures in situations like the 2019 flood event?
Defense is done with local and mobile defenses. Levels are measured by health points. Venice begins to flood at increasing rates exponentially already for a 20/30 cm rise, therefore even a simple low pressure causes the astronomical tide of full moon syzygies to attach to Venice. So Piazza San Marco which has an altitude of around 70-80 cm floods from 70/80 times a year up to 200/250 times a year. If instead I get up and go, always with respect to the historical zero, at 110 cm, here are the cases of flooding, which were once (up to the 70-80 years) up to 4 times a year, now due to the increase of sea level have reached a number of 5-6 times a year. The sea level has jumped, it has not grown naturally. You can see periods of oscillation and then a change of threshold, therefore as if the average rose in steps and then remained for 10-15 years. In the past 15 years we have had a 15 cm jump.

What is the closing value used in the operation of the barrier?

The closing value of the Mo.S.E. is 110 cm and Piazza SanMarco has an altitude of 70-80 cm. To avoid the flooding of the latter, local defenses are put in place. Currently, the management rule, which has been defined and approved at the executive project level but can be changed at any time if greater changes in sea level are observed, is that up to below the quote of 110, local defenses are provided. These are necessary above all in Rialto and SanMarco because they begin to flood at 60 cm. SanMarco is defended with 2 systems:

local defense of places with an altitude of less than 60 cm, in which flooding is allowed when the altitude reaches 80 cm to avoid under-pushes. It is therefore simply the reduction of saltwater damage in the Narthex area, that is the one of the Basilica. The local systems used are mainly the raising of the banks, because the water enters or through the drains at the level of sewer pipes, because Venice does not have a sewer and therefore the water can go back as a backwater that goes back; or as infiltration of the ground or otherwise as a surmount of the shore or of the margin that separates the decking from the water. These are the defenses only for SanMarco. The other areas of the old city have already been raised for the most part up to 110. SanMarco has had delays in raising due to its historical relevance.

At the threshold level as a whole there is a belt with the interception of all the historical exhausts, they are called Gatti in Venetian, with definitive closing systems so as to control the permeability and infiltration of the subsoil, so the square will be defense up to 110cm. Rainwater is intercepted and taken with the pumps out, and when the water then exceeds 110, the Mo.S.E. operates, otherwise the pumps must be kept active and constant because at that point there is no longer natural drainage. If 120 arrives and the Mo.S.E. does not start, wait for the pumps to empty everything.

What is the return period of the high tide?
At the time of the project, the return period of 110 cm above sea level, relating to the closing threshold of the Mo.S.E., was 3-4 times a year. Considering then that the three-hour forecast error, which is what makes the forecast irreversible, is 10 cm in 90% of cases, in reality it must be closed when there is a forecast of 100 cm. The forecasts were initially of the order of 6-7 cases per year. Although the project differs from the Rotterdam barrier, which is closed very rarely compared to the Mo.S.E. forecasts, it is also inspired by the idea of laminating the inflows during closure. Although the contribution of the important rivers has previously been diverted, even in Venice it is necessary to laminate the inflows because there is a flow that passes through the tunnels (between one sluice and another) and, in addition, the wind can make important improvements which, with closed sluice gates, could reach 60 cm. A dynamic adjustment is therefore necessary, imagining allocating such a volume so that during the storm surge the water inside does not grow more than the safeguard level. The rivers have been diverted but direct rain, wind and the flow that passes between the air gaps create this problem. The flow rate, of 30 m3 / s, is insignificant in relation to the fact that the maximum flow rate reaches 400 m3 / s even considering the full capacity of the pumping system, (because there are polders behind the Mo.S.E.). So, attacking all the pumps and putting all the gravity outflows that are inside the banks do not reach more than 400m3 / s peak, which as a precaution in the management model have been assumed constant and concomitant for a day.

How long did the flooding last in 2019?
Generally, a high tide lasts 3-4 hours because it is modulated by the astronomical tide, it drops every 6 hours and grows every 6 hours. Although the storm surge is constant for a day or two, it is found to be modulated by the astronomical tide and so, with the same high water reached and the astronomical tide of Syzygies, the most intense, the storm surge is less annoying because there is the possibility of having this modulation. In the case of 66, however, there was a strong storm surge in quadrature with a tide that moved little, in fact 66 was dramatic not so much for the dynamism of the event as for its duration, because it lasted about 24 hours.

Was the exceptionally high tide of 2019 forecasted?
Before the event, a high tide was expected but that exact value was not expected, rather a maximum value of 140-150 was expected.

How will the project cost, in total?
Mo.S.E. costs 6 billion and will cost 6 billion in maintenance over its 100-year useful life. Each year that passes costs in terms of avoided and not avoided damages, on average approximately 100 million, if we also add the additional 100 million of the barrier plus the lagoon environment management system, then if the Mo.S.E. is in the incomplete state and if not used, damage of 200 million per year is produced. This delay is therefore serious. The

damage was estimated at between half a billion and one billion euros. However, estimates have been made for years and must be discussed with the municipality. Initially he talked about a billion then he scaled back to half a billion. I believe that the people who have requested refunds to date are around 200 million because not everyone has finished the practice.

Could the barrier have been used to protect the lagoon from the 2019 flood event?
Presently, during the 2019 event the entire Lido mouth, the closest to Venice and the most useful, could have been closed. I (Giovanni Cecconi) estimated, with a mathematical model that the benefit derived from the closure of this barrier during the storm surge of 2019, would have been 35 cm precisely because of its impulsive nature. The hydraulic impedance, i.e. the ability to filter a fast transient if it is very fast, is very effective. It is clear that if the event is prolonged, then the whole lagoon leads to the level, even if from one mouth. But if it is a very rapid peak, as in this case, there would have been this unexpected benefit, I say unexpected because on average the benefit is about 10-15 cm but in this case it would have reached 35 cm, made with the mathematical model in which takes into account the boundary condition and wind forcing.

Did the barrier suffer any damage during the 2019 flood event?
During the high water of 2019, the barrier did not suffer any damage. The only damage he suffered was 5 years ago because, while the vestment was being built, the tunnel was flooded, and this led to damage to the pipes that were immersed in saltwater making it necessary to replace the pipes that are stay submerged in water. Instead the main technical problems concerned the navigation basin of the port of Malamocco, which has been closed. During the design, it was not taken into account that the basin was subject to wave motion, and therefore was not shaped to resist appropriately. The basin was designed to close in two minutes, so it should not interfere with port traffic. It was practically an air cushion on a beam, very light and not so much ballasted, and above all with an upward L-shaped facing towards the sea, then the wave from below raised it, putting it in vertical movement, and falling back it is broken. It was a classic design error because a Belgian or Dutch company was commissioned without anyone reporting that it was not a fast navigation basin for rivers, but that it was exposed to wave motion, so they did not really consider the latter.

Were there any other technical problems that caused delay in the project?

During construction in Chioggia there was another problem. While the concrete was being injected, a valve that had to let the concrete vent, when the entire formwork was filled, remained closed so the little volume that the concrete put in damaged the casing that had to be filled because it was stressed by an internal pressure well above the design pressure. This occurred due to a human error linked to a lack of control in these concrete relief valves. It was remedied with an expensive intervention, because a bell had to be built to create an environment in the air and do the work over the foundation box. Imagine a tunnel immersed in the bottom of a canal. Above the bottom it was necessary to build a reverse steel shell on which the water was removed, and the atmospheric pressure was sent with a turret from the outside creating this shell, a working environment suitable for repairing the concrete that had been injured.

What is the probability of failure of the barrier, once completed?
The risk that one of the gates out of 78 will not get solved is one out of ten thousand. However, failure to operate up to 1 or 2 barriers does not cause problems because there is the possibility of closing at a lower sea level, based on reliable forecasts, having sufficient volume to reduce the high water inside. If the malfunction is not known and a barrier closure is required, up to 1 or 2 non-functioning gates, depending on the duration of the event, have a negligible effect. The probability that there is a malfunction must be expressed in very precise terms, such as "What is the probability that there is 5-10-15-20 cm or more above the safeguard level?" This is a very important analysis because it affects maintenance and redundancy, and therefore the economic life of the barrier itself. The safeguard threshold can be exceeded in the city even in cases of intense rain or in places where the slope of the sidewalk is upside down and allows flooding of more or less 5 cm. Depending on whether the threshold is accepted or not, you can save or lose a lot of money.

It is a problem if there is a gap between the various sluice gates? because a wave effect is created so a slightly more intense flow occurs at that point.
Even if one or two sluice gates do not work, the barrier is still closed because the bottom protection is designed to withstand 6 meters per second. At De Borst, in the Netherlands, and there this configuration of 1 or 2 sluice gates

was tested, which do not lift, and a bottom protection has been made so as not to damage the barrier. However, the subject of subharmonic resonance has been studied and it is a catchphrase linked to the fact that they wanted to find technical reasons to stop the completion of the Mo.S.E.. The resonance, however, has been identified since 1992, in a conference in which Professor Chang Mei, who is the best expert on subharmonic resonance phenomena for marine structures, made statements on the safety of the barriers regarding this aspect. These problems can manifest themselves but once identified they are also easy to solve. The intrinsic safety of the Mo.S.E. that looks at the subharmonic resonance consists above all in the fact that the angle can be changed. If an undesired resonance occurs on the barrier at a certain angle, this can be changed in the face of a reduction in the seal which can certainly be remedied by closing the barrier early. Even if the sluice gate remains in indifferent balance and closes only 50% of the time, if a volume of 320km3 is closed for an hour before, this is a huge volume of leap available and, before the value fills up, they pass 6/7 hours and at that time the astronomical tide has time to drop and therefore the total level to be lower than the safeguard level. To make these observations it is very important to have a dynamic model that manages the lake, at variable initial levels in relation to the state of the barrier, whether it has all the gates or not, in relation to the forecast of the wind and in relation to the duration of the event, therefore how the forecast uncertainty can then benefit the defense and what is the cost, if the safeguard level is exceeded, if there are costs if the duration is extended. So, it's a system highly flexible that will find its optimal management by simply using it.

Are there maintenance actives to be started, since the project suffered such a delay?

Given the 5 years that have passed, the sluice gates of Treporti are to be removed, among other things in Treporti it was already expected that sand would be deposited (it concerns only the first 5 sluice gates) 10 cm of sand have already accumulated. An expensive vehicle was also foreseen, the same vehicle that cost 20 around 30 million can now be done with less than 10 million also because replacement means have been found in Holland, which do exactly this job. Unfortunately, the sand slips everywhere, therefore also between one sluice and another, creating the need for maintenance. Maintenance is done with dredging heads equipped with an umbilical wire camera that work like remote controlled vacuum cleaners that also have nozzles to make jets of water. In the offshore, they have been doing this for quite some time, yes, but let's say that the problem is more intense on the coast. while in the offshore there are the sand waves (therefore large volumes) that move, here it is more related to turbulence and we have two types of deposits: the material that is accumulates on the sluice gate which is coarse and which then slides down into the trench when the sluice gate is raised, and the fine material that goes into the cavity 15 cm each day and goes further below.

The serious problem can be given by the sand, however, because if the sand goes to get close to the hinge it leverages, and it is like when someone slams the door and there is something between the hinge. It is a disadvantageous lever and since my arm is much more advantageous than the arm that offers the door, it skips the pivot and therefore the door breaks. This is what can happen in the Mo.S.E..

What would happen if maintenance is note done regularly?

A study was conducted in 2006 which was later reported in the international meeting that took place in Svolle (I think) 6 years ago. In that year a lift had been tested and then, in putting the gates down again, these had not descended to a horizontal angle, they had remained with variable angles around 5-3 degrees, a very small amount. The important thing is that the sluice is not supported by sand near the hinge so the area near the hinge must be cleaned. An alternative that had been designed was to put pieces of rubber, to extend, to prevent the sand from sliding near the hinge when the barrier is raised. With regard to the deterioration of the sluice gates, disassembly and complete painting and replacement (delian) of the sacrificals they are equipped with is foreseen every 5 years. About 20 tons of zinc are consumed every year on all mouths. A zinc-like number that is released into a port by all ships entering and leaving. The more you pull the more you create a queue on maintenance. Since each sluice takes one month and since maintenance can only be done in summer, if the sea level increases, the number of closures increases, the summer periods useful for maintenance are shortened, this can be a risk to be faced, or with faster maintenance or with maintenance requiring longer maintenance intervals.

Who would take care of the maintenance and the operation of the barrier?

Management and maintenance have yet to be put out to tender and currently there is also no funding from the state, and this is very important because it is a critical fact. Usually when a work is finished, we already know who will manage it, we talk about commissioning and testing, in project management they taught that the final parts of the commissioning are done together with who will manage the work. There is great damage related to the incompetence of management of this aspect. If the management and maintenance of a work is done by an agency that has not had previous contacts with the work, a large part of the operation time is spent by the company to understand the functioning of the system. If you want to think badly you can think that they want to do it (the designer, the commissioner, the consortium, the magistrate for the waters, the port authority, the management, the municipality of Venice, citizens' organizations ...). The Water Magistrate had an important role within the management and continues to have it, the name was changed because after the scandal happened in 2013-14 the government, through a measure, simply changed the name and closed the magistrate. This was only a facade measure. No implementing decree has followed this provision, leaving the metropolitan city, originally in charge (of management?), Has never been in a position to continue. It is important, now more than ever, to be able to create opportunities for contact between entrepreneurs who can have a pleasant, shareable idea of the future and on this to build and activate actions, can be the innovation that is needed at this moment. It's called the anticipation of the future technique; it is a technique that is often used. In Italy there is an excellent school on anticipation systems active, there will also be in Holland, and I (Giovanni Cecconi) believe that these are the tools that we must use at the moment.

What are the operational criteria followed to operate the barrier?

The forecasting and management systems require that the barrier be raised in advance to the pre-established levels. If it is a normal event that lasts 3 hours, just close at 100 m. This forecast dilemma is less complex in nature than the dilemma of warning a person to return to Venice because his car, which is in the garage, will be flooded. In that case it is necessary to predict whether or not it will have exceeded the level at which the machine was put, and therefore in practice the probabilities of exceeding all the thresholds. Given that people can have goods placed at different heights and with different consequences that are not known, decisions on their behalf. This is the dilemma of playing the siren and warning. The dilemma of closing the barrier is easier because I don't care what level will be reached, I am interested in whether or not the 110 cm threshold will be exceeded in a striking way. And so, this means that my theoretical fear of not knowing how to manage the barrier is actually enough that it is closed when the level in the norm exceeds 100 in Lido, measured therefore I don't have to assume anything. If I want to be good at managing and predicting those extreme events that last a long time and that can create serious problems due to the duration of the prolonged closure, then whenever there is a hint that foresees an intense and prolonged event, revealed by the interpretations of the images satellite, then in that case I close at 60, creating a huge rolling tank, leaving it closed until the level drops to a normal value. The only problem related to these early closure decisions is that the port must be notified 3 hours in advance. This is because if ships leave, they have no evolution basins, and they cannot go back. It would be enough to build the basins of evolution and at that point everyone would be happy. Absolutely no forecast would be needed, only a level meter. If instead it is decided, as has been done, to disturb the port 3 hours in advance, the port is irreversibly advised to stop the traffic. Clearly with the navigation basin this involves not only a blockage of the port but also a delay on maneuver times which instead of lasting 4 hours there will be 2 hours more, therefore they will be 6 hours, but as a percentage of the traffic on the Adriatic which it also lasts a day, if the traffic logistics are well organized both since the ships arrive throughout the ship cycle to affect the Adriatic, the marginal value is negligible. Clearly the only effect is the halo effect, that is that nearby ports take advantage of the penalty that the barrier imposes on the port of Venice, attracting trade and tourism.

At what threshold will the barrier stop being effective?

The sea level threshold, beyond which the barrier becomes inefficient, in terms of sea elevation and 2 meters (66 high water) + 50 cm of the astronomical concomitance (which was not in 66) + 50 cm of sea level growth, + a franc of 50 cm, before 3.50 m of sea level nothing breaks, if you go further: if I don't lift it won't break anything, but if I lift everything and go further I could, however, the system is intrinsically safe because the buoyancy thrust cannot keep more than 3.50 m of sea, therefore the gates fold and consequently the thrust is reduced. In that situation the hydraulic seal is lost but there is still a lamination. If there is good system management and the barrier is closed at minimum and low tide, the water could theoretically be kept below 110 cm.

A sea level rise of 60 cm or 50 cm is already sufficient to send the system into crisis. If this, instead of happening, as was foreseen, at the end of the century, happened before and I was not able to raise local defenses, this would mean shortening the life of the work by 20-30 years. Clearly, this would only happen if local defenses cannot be implemented. Implementing local defenses is equivalent to accepting 20 cm more than the rise in sea level. In another scenario in which the port did not accept to always pass inside the navigation basin, the lagoon has anoxia effects (surreal scenario because the lagoon is unclean and the closures are very short and when I reopen I can open in a differentiated way to create residual currents and change the water) deriving from the prolonged closure of the barrier in summer, we are faced with a useful life of the minor barrier. The surprise is this: if the sea level increases by 50 cm in 40 years, compared to the forecast to grow 50 cm in a century, the benefit doubles because I will have, in a shorter useful life, double the events that I would have had in the double life. Now the cost-benefits of the work in terms of avoided damages are equal, therefore 1 on 1 (the work costs me just as much as the cost of the avoided damages) with the current sea level [this is a study done by the University of Padua that between the other is online]. In this havoc, however, an adjustment to the goal of the useful life is to be rescheduled. This is a journalistic discourse: “If sea level rises, is it better or not to do the Mo.S.E. or finish the Mo.S.E.? Or does it become useless even before its completion? The answer is that it is twice as cheaper if sea level rises, other conditions being equal. Then I can put in place all those flexibilities that have not been explored that deserve more attention. You can, for example, re-engineer the project and invent many new things. The basic cost is the foundation, if this foundation, other devices (gates in rubber or other materials) were then placed, giving up a strength, rigidity and formal strength for a substantial ability to reduce flooding, they would open an infinite number of possibilities, already having the frame ready. I have a foundation, two tunnels, i.e. an anchor base on which I can put anything. You can, for example, narrow your mouth and keep only two sluice gates. However, these things would require intervention, at a lower cost because the foundation is already there, but it would clearly increase short-term effectiveness. One of the hypotheses that was wanted to be made, but has not been made, is the Rotterdam solution, but not made with the sluice gates that rotate but with a train that had vertical sluice gates, therefore similar to tracks and a train. This solution was discarded, however, in 1988, because it was necessary to dismantle the Austrian forts that are at each port mouth (Venetian fortresses of the 500). At the narrowest point, which was the patrolling point, there are also these historical forts and therefore this solution implied going to overturn these monuments. Since it was a period in which not everyone was in favor of the Mo.S.E., undertaking a solution, even and the most economic, which provides that the sluice gates are in use when they are in use, as in Rotterdam, it was an impracticable way from the point of view of approvals. So faced with this dilemma, the president of the Venezia Nuova Consortium at the time, who was Zanda Loy (now head of the Senate) decided to give up the Rotterdam-like solution, which now fills the newspapers.

What about biofouling?
As for Biofouling, the best painting that exists in the world comes from Japan, precisely from Hiroshima and is called Shogun Marine Paint. It is a paint that, without having toxic materials for the environment, produces an angle of 150 ° of surface tension so that anything slips away from this paint. It is clear that painting must not be damaged because it is precisely its texture and microstructure that gives it this property. Then you have to make the jet of water at the right pressure to remove the patina of mud that is deposited on it so it is true that the paint is good, but in the places where there is no current of water and where there is a mud deposit, that mud above can make a windy effect which can then facilitate the arrival of oysters and other organs and snakes or other organisms that can attack, so it would be good that the sluice gates were sprayed from time to time.

What is the maintenance plan?
Schedule of routine maintenance was initially a sluice gate per month, but with two means. Since the medium (jackup) is expensive and also had problems, it was eventually decided to build only one instead of two. One of the problems to be planned in the medium to long term is the second means of maintenance and the speed with which the work is done. If the maintenance system can only hold two sluice gates at a time and you have 80 sluice gates, you need to build a logistic system, from this you can see that I need a certain number of months which I think are 7 or 8 per year to be

able to respect the once every 5 years maintenance, such as maintenance frequency. So if the time windows for maintenance are restricted based on this, the capacity of the plants must be doubled. If, due to rising sea levels, you are no longer 7-8 months old, this becomes a problem. Here, this is one of the reasons that led to prefer the Rotterdam model, and was the subject of discussion of those who supported the train. We must also imagine that the flexibility that the system has is used. Clearly the problem a can become a challenge and an opportunity for innovation, or it can be a bogeyman who is shaken to make decisions that still involve costs, given that we are 95% complete. Maintenance management is therefore a problem because it affects cost, finance. Since it is not yet approved the law regarding maintenance and management of the barrier, people should be committed, while finishing, to redesign with other objectives, which are not those of the time, and which were dictated by other things. This should be done with minor changes to the current system. The economic analysis that must guide this process can lead to the replacement of certain systems or components that are now expensive to maintain.

What is the protocol followed in case of exceptionally high tides?

The protocols for protecting the lagoon and the city in crisis cases like this are to notify the port three days before, in anticipation of a high-water event greater than 110 cm, and therefore greater than 90 cm because three days before it is 20 cm in less. The technicians in charge of management must go to the site and put themselves in stand-by condition to follow the approach of the expected event hour by hour. The system can consider the arrival of one or more repeated events, because an annoying scenario is one in which one event immediately follows another. You cannot manage one event at a time therefore, there is this warning of the forecasting system which has already been installed and which works, which I (Giovanni Cecconi) managed for almost 10 years. This forecasting system has examined in virtual reproduction virtualizing the barrier, all these procedures and therefore we already have data that tell us if the forecast, the forecast error and the rules adopted are useful or not to avoid flooding. It has been seen that none of the cases would have been such as to flood Venice above 110 cm if the system had been operational and with the known levels of reliability. As you get closer to the finish, you then come to a point where the forecast error is reduced, so you start to worry if the water level will exceed 100 cm in Venice and 120 cm in Chioggia. Chioggia is defended locally up to 130 cm above sea level as it is 20 cm higher than the Bora wind rise. So, to avoid closing the barrier too often to defend Chioggia, the latter has a higher local defense than Venice and the demand for closure can be rebalanced both on Venice and Chioggia. The decision takes place three hours in advance, and the port must be advised to block the port, at that moment the intention to close was confirmed, which I had previously communicated in a preventive but uncertain manner. There are therefore two cases:

- It is said to keep the closure and then I do not close because the level does not exceed the trigger level, ask for 100 cm, but the high tide comes anyway.
- When the level exceeds 100 cm, I usually close the barrier. Unless it is an exceptional case, in which the trigger level is moved to 60 cm. Imagining that all these things have been foreseen, but the level stops at 99 cm, in this case I produced an unnecessary stop of the port because I did not close the barrier.The port in that case is blocked too far in advance And the ships may find themselves in a position to not be able to face the back.

Given that both cases are unwanted, and that the first case has a much more significant impact, one has to have a number of cases where the port has been blocked without the high tide occurring. Since there are five per year in excess, the port could be closed about 12 to 15 times a year, almost three times more than the high waters that exceed the safeguard quota due to this caution linked to errors forecasting. Furthermore, however, the closures could be double because I close at 100 m to avoid 110 cm, but the water would have reached 108/109 cm. So, there is a whole number of cases of unnecessary closures or unnecessary birth notices and this percentage is important because then it goes to weigh on the annoyance that the barrier gives to the port. But having a navigation basin, only delays or prolonged arrests are transformed.

Appendix O - Interview with Alberto Scotti

Interview with Alberto Scotti, the Designer of the barrier, from Technital company

Interviewer: Fabio Tonacci for the newspaper La Repubblica, retrieved from https://www.oice.it/626902/technital-scotti-intervista-sul-Mo.S.E., conducted on 16/11/201

The Mayor of Chioggia claims that, if the barrier would have been operated at at Lido inlet at least, the damages to Venice City would have been reduced

He doesn't know what he's talking about. Technically, it was possible to rise the gates, but then the barrier wouldn't have been able to hold the tide, because the system isn't ready.

What do you mean?

To rise the barrier in half an hour, as i twill be once the barrier will be completed, three compressors are needed. At the time we had only one, it would have taken us five hours to raise the mobile gates, it wouldn't have made sense.

The day before, you knew that a high tide was coming. Couldn't you plan an operation then?

The Mo.S.E. can be operated only when the water level reaches 80-90cm. It should not and must not be operated before. Anyways, even if the barriers Lido and Chioggia would have been risen, leaving Malamocco, where the test detected vibration problems in the conducts, open, not much would have changed: maybe 10 cm less compared to the 187 cm that we encountered.

Didn't the warning system impose to at least try?

The decision was very much suffered. Don't think that me and the two commissioners of the CVN don't feel the responsibility of the decision on our shoulders. In those conditions, however, it would have been crazy.

What was at stake?

The flooding of the galleries where the technicians work. Without final testing, and with only one compressor, the sea would have overcome the mobile gates from the top.

When did you take the decision?

The day before, on the phone. We knew that we would have a high tide of approximately 150-160 cm, not 187 cm for sure. Facing that information, I am happy with our decision.

Was it a unanimous choice?

The attorney Friengo agreed to the possibility, but nor me nor the engineer Ossola thought it was a real hypothesis. I understand the politics pressure, because people are exhausted, but the Mo.S.E. barrier cannot still be operated in safety.

The Prefect, the civil Protection or the Ministry, in theory, could have obligated you to operate it.

If someone would have imposed it to me, I would have gotten away.

But you must understand the nervous attitude of the citizens towards a project that had been talked about for 30 years, which costed almost six billion euros, and still not completed.

At the time of Giovanni Mazzacurati, the CVN would release Gantt Charts totally impossible to comply with. Now we have a realistic delivery time: 31 December 2021. This time we'll going to make it.

How is it that the project is taking yo uso long?

You forget that the funding for the works were not always granted by the state. Around 2008 they stopped proving us the funding and the CVN had to ask for an international funding to continue with the project. Then there was the legal investigation, which to me was completely fair, but resulted in the getaway or the bankruptcy of many big firms that were working to construct the Mo.S.E..

I repeat, the investigation was totally rightful, however not Condotte, Mantovani, Fincosit companies are no longer there and this slows down the construction process. It's inevitable because the Mo.S.E. is an innovative and complex project, it is not like a simple project in which is easy to alternate firms without too many consequences. It was wrong to think that this legal procedure wouldn't have brought delay.

Even now, though, it does not seem like you are working at full speed

The Provveditorato of the Veneto Public Works is not providing us with the funding necessary to fix the errors that the investigated firms have made to the project and the firms have disappeared. Where are we supposed to find the money to fix all those problems they made?

Did they ruin permanently the Mo.S.E. project?

No, but they left behind scabby consequences. For example, now the air conditioning in the three underwater galleries, which should have been the first thing to do, now it appears to be the last. Even the corrosion of the gates hinges is partially due to planning errors.

.

Wanted errors, to make money out of?

For ignorance, really. They weren't experts in the field, and they took decisions based on the company's economy. Now, there is no turning back.

Anyways, the cots for the project are absurd.

If we compare it to similar barriers build all over the world, they cost twice as much.

You planned for a third of the total cost that the state had to take care of. Don't you have anything to say about that?

You are right. Here, however, we talk about an innovative hydraulic system like no other in the world. It was impossible to estimate precisely the final cost. Even all the technical problems that we encountered, are normal for a project of this size.

Many people think that the Mo.S.E. system is already obsolete, because thought of in the 1980s, when the global warning effects on the sea levels were undervalued

We had done researches and studies up until 2000. The Mo.S.E. is a dream coming true: it meets the objective of defending Venice without being visibly noticeable. It will work even with high tides of 3 meters and i twill not turn the lagoon into a marsh