Piera Alta

Facilitating pedestrian mobility in Venice during floods

AN INTERACTIVE QUALIFYING PROJECT REPORT
WORCESTER POLYTECHNIC INSTITUTE

Submitted by:
Rafael Angelo
Andrea Chan
Daniel Hill
João Maurício Vasconcelos

Project Advisors:
Prof. Fabio Carrera
Prof. Michael Aghajanian

ve14-alta@wpi.edu
https://sites.google.com/site/ve14alta/

Authorship

Each member contributed equally to the writing and editing of this report and all sections.

Acknowledgements

The Piera Alta team would like to acknowledge the following for their contributions toward completing our project.

Fabio Carrera - for his advising, assistance, and insight throughout our working period
Michael Aghajanian - for his advising, assistance, and insight throughout our working period
Georg Umgiesser and ISMAR - for lending us their time and resources
Oreste Venier and Eraclit Venier, SpA - for lending us and assisting us with the Cleverpole
Lorenzo Bottazzo, Luisa Facchin, and Insula SpA - for providing data on pavements
Dylan Kirby - for his assistance throughout our working period
Robert Traver - for invaluable advising and helping us get a strong start on our project

Abstract

Piera Alta explored the possibility of facilitating pedestrian flood routing in Venice, Italy through a mobile web application. To address the issue of flooding, data from previous years were first examined to show the rising trend of flood frequency. Water levels were compared with pavement heights. Working with several agencies, the team was able to achieve a strong understanding of the behavior of tides within the islands of Venice and how floods may occur by using mathematical models and a tide sensor. The team created web visualizations to demonstrate these findings. The information obtained was incorporated into the design of the mobile web application. Furthermore, a mockup of the web application was created to assist those that may look toward its future implementation.

Executive Summary

Due to its geographical location, Venice has always been subject to the ebb and flow of tides. Data collected from *il Istituzione Centro Previsioni e Segnalazioni Maree*, or *il Centro Maree*, shows that tide levels are rising each year. When the tide gets high enough to invade the pavement, this is referred to as *acqua alta* – high water. This phenomenon occurs at different water level heights throughout Venice, but *il Centro Maree* defines a high tide as *acqua alta* when the level surpasses 110 cm. According to *il Centro Maree*'s data from 1966-2009, "high water exceeds 110cm, on average about four times a year" (Bon, n.d.). By looking at their data, it is possible to see, as shown in **Figure 1**, that the frequency of *acqua alta* is increasing. *Acqua alta* is creating more inconveniences for pedestrians that wish to avoid floods. The Flood of 1966, which flooded about 90% of Venice, caused the city to actively begin taking measures toward flood protection. *Il Centro Maree* was founded as one of these preventative efforts. Today, this government agency gathers information on tides at *Punta Salute*. This location serves as a reference point for the tide level throughout Venice. There, they have a station housing a tide datalogger to measure tides. The information from *Punta Salute* allows *il Centro Maree* to come up with forecasts. Tide forecasts are represented in three parts: astronomical tide (moon and sun), meteorological tide (wind and barometric pressure) and predicted tide (sum of astronomical and meteorological). These parts are used to create a graph (see **Figure 2**) that displays the forecasted tide (*marea prevista*) as well as the astronomical tide (*marea astronomica*). The forecasts are updated every 24 hours and predict the tide trend for the next 72 hours. Knowing the current and future tides at any given moment is important, but more important is understanding the ins-and-outs of how tides work.

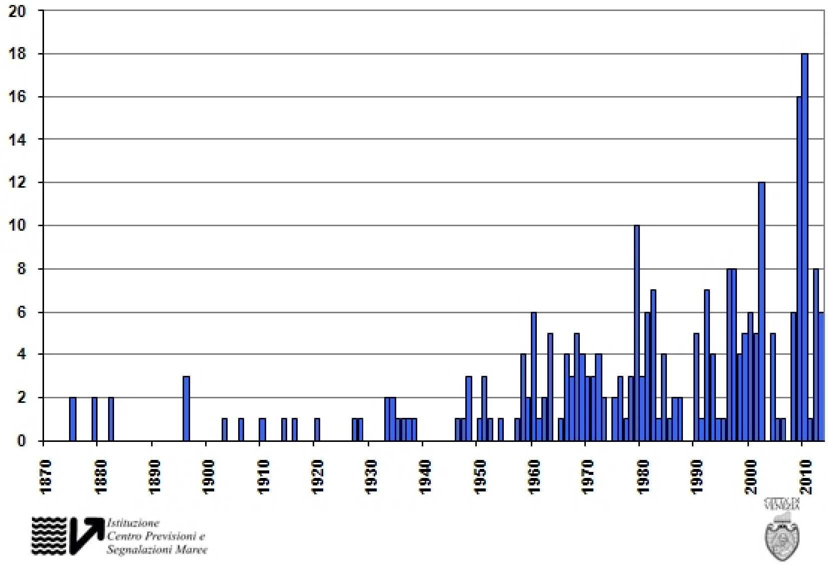


Figure 1. Graph showing the increasing frequency of acqua alta

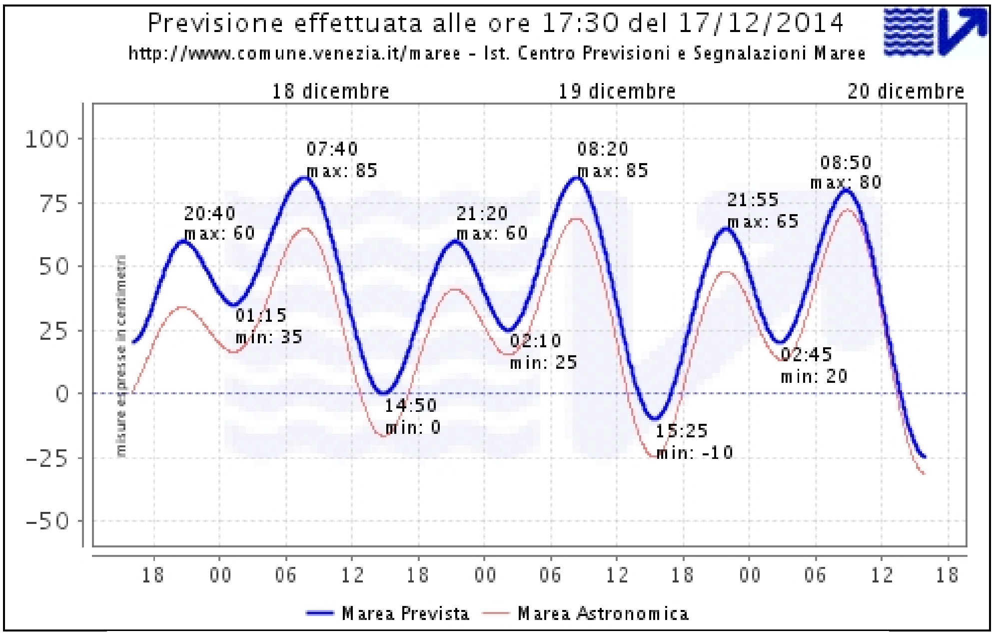


Figure 2. Graph showing the predicted and astronomical tides

In 1923, the *Consiglio Nazionale delle Ricerche* (CNR) was founded. In 1969, CNR established the Institute for the study of Dynamics and Large Masses (IDGM). IDGM would eventually be incorporated into the Institute of Marine Science (ISMAR) ("*Venice in Peril* – Scientific & Research"). ISMAR has dedicated much of its resources to studying *acqua alta*. Through these efforts, ISMAR was able to develop a Canal Hydrodynamics Model. Their model takes forecasts from *il Centro* Maree and produces the water levels in the inner canals of Venice.

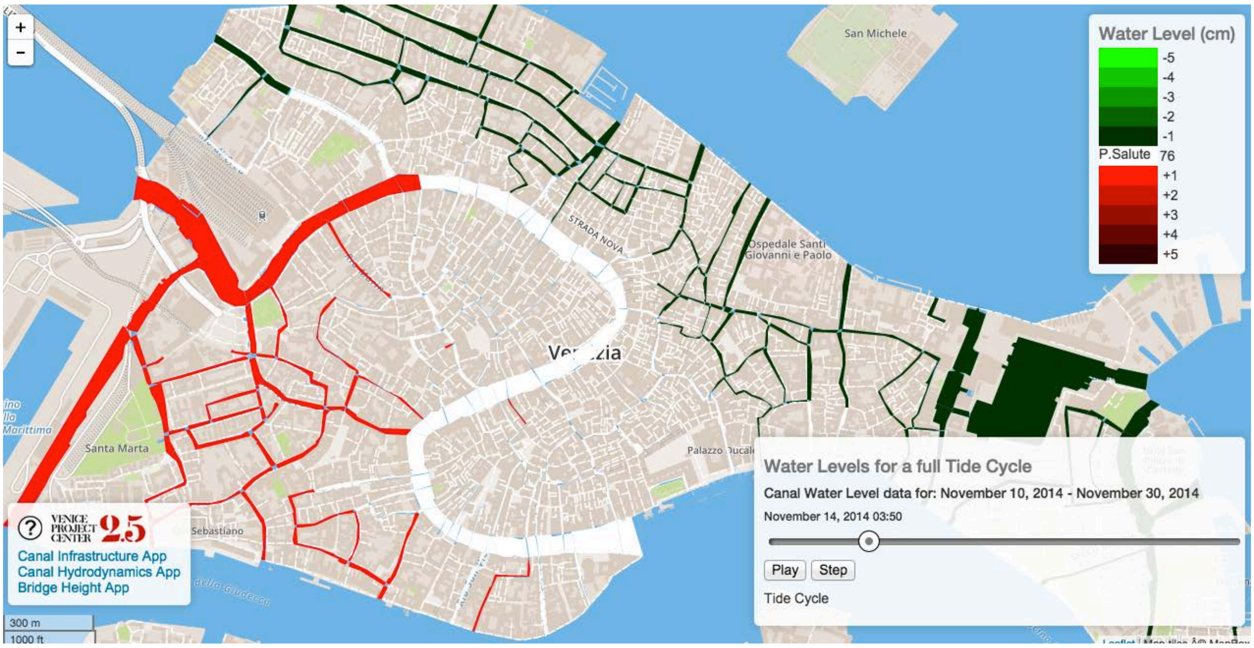
Insula, SpA began taking preventative measures against floods by raising the pavements. Even though it changed how tides affected parts of Venice, raising pavements did not eradicate floods and still posed problems of its own. Insula also worked on mapping the city of Venice to determine the heights of pavements. They did this through their *Rilievo altimetrico, modellazione spaziale e scansione* (RAMSES) project. The pavement information can be used to determine whether or not an area floods by comparing elevations with current tide levels.

The idea of installing flood gates at the entrance to the Venetian Lagoon from the Adriatic Sea has been alive since the early 1980s. This idea became a reality in 2003 under the title "MOSE." MOSE aims to install flood gates at the three inlets from the Adriatic Sea to the Lagoon. When completed, the gates purpose will be to stop tides above 110cm from entering the Venetian Lagoon. Currently, completion of the gates is projected for the year 2017. The MOSE project is expected to stop floods from occurring in the majority of Venice, but will not solve the problem completely. Floods are a part of Venetian life that may never change. Instead of trying to stop nature there are those that stride toward making information about tides more accessible.

There are many applications that serve to inform pedestrians about *acqua alta* and floods. The majority of these applications uses either the current tide, tide forecast, or both from *il Centro Maree* and publish them. Some of these applications include elevation levels of popular areas along with the current tide. Others map out where they believe floods should be at that time based on comparisons between elevation levels and current tide levels. Displaying this information to pedestrians in a way that is easily accessible is important, but there is one major flaw with all of these applications. The only tide level they take into consideration is that at *Punta Salute*.

The goal of Piera Alta was to design a mobile web application that can route pedestrians around flooded areas. Users of our application can enter a start and end point, and the application will show them a path that will get them there without walking through flooded areas. What sets the Piera Alta application apart from others is that it combines information about current and future tides, tidal latencies, and mapping software. With this combination, our application allows pedestrians to get from point “A” to point “B” without getting their feet wet.

To achieve our design goal, we updated ISMAR’s Canal Hydrodynamics Model. The updated Model takes forecasts from *il Centro* Maree and runs them through a simulated Venetian canal system. The tide level in any canal at any given time is displayed in reference to Punta Salute. The 72-hour simulation, sent to us from ISMAR, is run through the Model. Updating the Model allowed us to see how the tides move through Venice, where the water enters, and where it leaves. By updating ISMAR’s Canal Hydrodynamics Model, we were able to visualize and understand the inner workings of Venetian tides. **Figure 3** provides a screenshot of one of the visuals created by the team. The full app can be accessed through the Venice Project Center website.



Water Levels for a full Tide Cycle

Canal Water Level data for: November 10, 2014 - November 30, 2014

November 14, 2014 03:50

Tide Cycle

Figure 3. Water Level Delta App

To verify *il Centro Maree*'s forecasts and ISMAR's model, Piera Alta used the Cleverpole along with a meter stick to measure the tide levels. Cleverpole is a tide sensor that was loaned out to us by Eraclit Venier, SpA. The sensor provided us with important information on tidal latency and time delays. The measuring stick served as a way to determine the elevation at which the sensor was installed by measuring between current tide levels (from *il Centro Maree*) and the pavement heights from Insula, SpA. With these devices, we were able to learn important behaviors of tides at five locations throughout Venice – two in *Castello*, one in *Cannaregio*, one in *Dorsoduro*, and one in *Santa Croce*. The tides were monitored during the full, new, and half-moons. **Figure 4** shows the output of the sensor for the *Santa Croce* region relative to *Punta Salute*'s tidal behavior. These moon phases correspond to important parts of the tide cycle, and were our time windows for sensor installation.

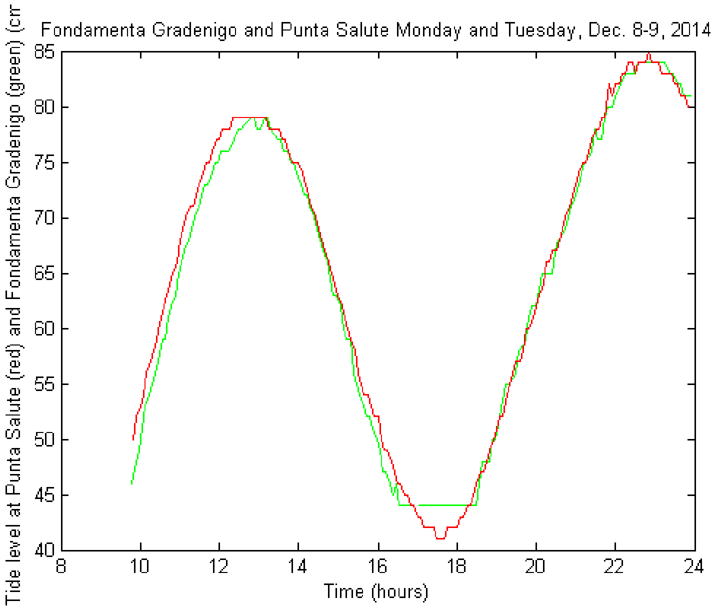
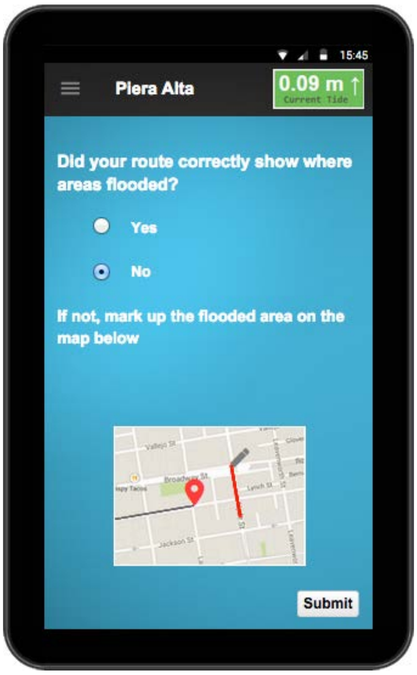


Figure 4. Sensor output (green) vs. Punta Salute *(red)*



Did your route correctly show where areas flooded?

○ Yes

● No

If not, mark up the flooded area on the map below

Figure 5. Flood report

With the information gained through tide monitoring, we were able to verify ISMAR's Canal Hydrodynamics Model and improve our app design. We discovered that the forecast outputs from *il Centro Maree* tend to not always be correct. Factors such as meteorological conditions and tide latency affect the actual tide level. The mobile app design accounts for these tide latencies. In addition to this, the app will feature a crowd-sourced feedback function that allows users to correct the flood status of streets. **Figure 5** shows the implementation of this feature.

Contents

1.0 Introduction

With no cars or bicycles, walking is the most common mode of transportation in Venice. For a city with such a high walking rate, Venetian pedestrians are susceptible to congested paths due to the large number of tourists and to the effects of incoming tides due to its location in the Venetian lagoon. These high tides can cause flooding and impede pedestrian mobility. For example, in 1966, the water level rose to 194 cm, nearly submerging the entire city. Since then, *acqua alta* (high water level) has been actively recognized as a major concern as it has been causing problems with “transport and pedestrian use of roads” (Bon, 2014).

Previous WPI research teams have made significant contributions towards addressing the effects of high tides in Venice. Unfortunately, Venetians and tourists are still regularly affected by the periodical high tides within the islands. An important step towards helping the people of Venice to plan around the high tides is the distribution of information on tides. To do so, different organizations have developed mathematical tide models that allow them to forecast the movements of the tides days ahead. For example, the *Instituzione Centro Previsioni e Segnalazioni Maree*, a government organization, provides tidal forecasts that are widely used throughout the city via their website and several mobile applications.

A partial solution to *Acqua Alta* was to raise the height of all of the pavements in the city. After the great flood of 1966, many institutions came about prevent the city from flooding and one of their projects was to raise the pavement levels in the islands of Venice. However, this project was costly and had its own limitations. In 2003, the *Consorzio Venezia Nuova* (CVN) started developing the MOSE project. The result of this project is a set of 78 flood gates that control the amount of water coming into the Venetian lagoon at three major water inlets. Once the MOSE Project is completed, there will be less risk for flooding because the gates close for tides at and above 110cm to prevent additional water from coming in (Kable, n.d.). Although they will be less frequent, floods will still happen in the lower parts of the city, such as *Piazza San Marco*.

Although a wide range of tide information has been distributed, the Venetian population still lacks precise information on where the floods will happen. The main deliverable of the Piera Alta project is to present a viable design for a mobile web application that will help pedestrians find a dry path between two locations in Venice, if such a path exists. The application will use the forecasts acquired from a combination of ISMAR’s lagoon model and canal hydrodynamics model, as well as real time tide information acquired from *Il Centro Maree*. This information will then be compared to the pavement elevations and, from this comparison, determine which streets are flooded.

2.0 Tides in Venice

As water from the Adriatic Sea spreads through the Venetian lagoon, it imposes unique infrastructural problems on the city. Its canals are highly influenced by the ebb and flow of the tides from the Venetian Lagoon. During times of high tide (*acqua alta*), canals are engorged with water to the point where some cause street flooding.

2.1 Historical Background

Since the 6th century A.D., there have been studies and reports of the water level rising and flooding parts of the city. Scientific research on tides began in 1867, when measurements of the tide were taken between high tide and low tide. The measurements were published as part of a government-issued report in 1961. Only recently, however, has the Hydrographic Office of Venice used the data to study the tides of the Adriatic Sea. Later, by studying the differences in pressure and directions of the wind, the Office was able to forecast tidal behavior (Bon, 2014).

In spite of a growing ability to predict flooding, no one foresaw the destructive flood of 1966. Due to "an abnormal occurrence of high tides, rain-swollen rivers and a severe Sirocco winds", the water rose to a record-breaking 194 cm. St. Mark's Square (*Piazza San Marco*) was covered under 150cm of water. The flood caused many residents to move out of the city in search of a more stable lifestyle ("Venice 'high water' floods 70% of city," 2012) and caused six billion dollars' worth of damage (Sood, 2011). The city's need for applied research and structural renovations was urgent.

2.2 Tides

Il Centro Maree bases its tide forecasts and measurements off of a single reference point, called *Punta Salute*. The tides are measured using a multifunctional datalogger, DA9000.

"The displayed data, updated every 24 hours, come automatically from the [observation station] and do not suffer any validation process by the staff of the Tides Center" (Bon, 2014). This data is used by *il Centro Maree* to generate tide forecasts. These forecasts are placed into an XML file and used to generate a graph. The graph, water level [cm] versus time [hr], consists of two lines - *Marea Prevista* (expected tide) and *Marea Astronomica* (astronomical tide). See **Figure 2** for an example of such a graph. The datalogger is housed at latitude 45 ° 25 '51.45309 "N, longitude 12 ° 20 '13.38616 " (Bon, 2014).

Figure 2.1. Multifunctional Datalogger

There are two variations of tides - spring and neap. According to the National Oceanic and Atmospheric Administration (NOAA), the type of tide present depends on the position of the sun and moon relative to Earth. Spring tides occur during full and new moons, when Earth, the sun, and the moon are in alignment. These moon phases result in exceptionally-high high tides and exceptionally-low low tides. Neap tides occur during half-moon, when the sun and moon are at right angles from one another. During this lunar phase, tide levels are moderate. Two sets of spring and neap tides occur during each lunar month. An accurate collection of data must reflect occurrences of both spring and neap tides and their effect on time delays. Each type of tide will have its own time delay with respect to *Punta Salute*. Measurements at various locations in Venice during spring and neap tides will provide information about how lunar phases are important to high and low tides.

Tides are not only controlled by the astronomical effects of the moon and sun. In fact, tides are also heavily affected by meteorological conditions. According to the Australian Government Bureau of Meteorology (BoM), there are three constituents of meteorological tides - barometric pressure, wind, and *storm surges*. Under high barometric pressure, water levels are depressed. The opposite occurs under low barometric pressure, with elevated water levels. This is known as the *inverted barometer effect*. As the Australian BoM states, the effect of wind is “variable” and “depends largely on the topography of the area.” Generally, sea levels will rise in the direction the wind blows - a happening known as *wind setup*. A storm surge is defined, by the Australian BoM, as a “pronounced increase in sea level” as the result of “the combination of wind setup and the inverted barometer effect associated with storms.” *Negative surges* result from a combination of high barometric pressure and offshore winds and are a cause for unusually low sea levels.

Tide levels in Venice’s canals may differ from what *Punta Salute* outputs. The

Figure 2.2. Station at Punta Salute

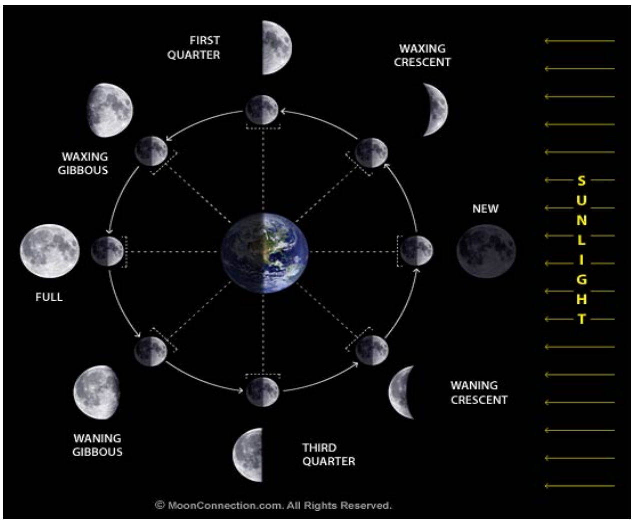


Figure 2.3. Lunar Phase

tides experience time delays based on their geographical location. Put simply, locations east of *Punta Salute* will reach peaks (high tide) and troughs (low tide) before *Punta Salute* and locations west of *Punta Salute* will reach peaks and troughs after *Punta Salute*. This phenomenon can be explained by the hydrodynamics of water entering and exiting the Venetian lagoon. The flow of water from the Adriatic Sea is from east to west. Therefore, the water levels east of *Punta Salute* will rise and fall before this point of reference does. Logically, this means that westward water levels will rise and fall after *Punta Salute*.

2.3 Sea-Level Rise in Venice

Geological and manmade factors are causing different changes within the Venetian Lagoon. Although geological factors play a role in the changes, the main causes are manmade factors. Ammerman (2005) writes that these include, “man-induced morphological changes” and “man-induced subsidence”, such as the water “pumping of groundwater at the industrial complex of Porto Marghera” (p. 107-115). These factors have resulted in a 23-25 cm increase of the water level in the last century (Ammerman, 2005, p.107-115). Studies have shown that the rate of change in sea level between 4000 BC and 400 AD was estimated at 7 cm rise per century and 13 cm increase per century between 400 AD and 1897. This rise in sea level has resulted in an increase in frequency of floods through the centuries. In the 20th century alone, the frequency of floods increased about sevenfold. Not only does this sharp increase cause damage to Venetian monuments and landmarks, but it has also proved to be a great obstacle to both citizens and tourists in the city (Ammerman, 2005, p.107-115).

2.4 *Instituto di Scienze Marine* (ISMAR)

On the forefront of tidal research is the *Instituto di Scienze Marine* (ISMAR). ISMAR conducts research on various aspects of oceanography, including Venetian high tides. One of their responsibilities is to manage the Acqua Alta tower. The tower was installed on January of 1970, and it is among the earliest advances to prevent high tides in Venice. “The main objective was to obtain information about the meteomarine conditions off the Venice lagoon, where the old town is threatened by ever more severe flooding“ (Cavaleri, 2014, p. 29-70).

The Acqua Alta tower, however, cannot, be used to directly measure tide levels in the canals of Venice. It is used for weather and storm forecasts. Using data acquired from the tower, ISMAR was able to develop the Shallow Water Hydrodynamic Finite Element Model (SHYFEM). SHYFEM is a “program package that can be used to resolve the hydrodynamic equations in lagoons, coastal seas, estuaries and lakes" (ISMAR-CNR, n.d.).

Using SHYFEM, ISMAR was able to develop a two-dimensional finite element model of the Venetian Lagoon. Georg Umgiesser (2004), one of the developers of the Venetian Lagoon model, explains that the "model uses a staggered grid for the spatial integration of the water levels and velocities." The lagoon model was used to provide data to a browser-based canal hydrodynamics model developed by ISMAR and a group of Worcester Polytechnic Institute (WPI) students (Venice Project Center, 2013). The canal model was used to demonstrate current velocity and direction in the canals of Venice over a period of one week. The canal model outputs information about water levels and flow.

The canal hydrodynamics model is a FORTRAN application that must be compiled on a FORTRAN compiler using a Linux system (Venice Project Center, 2013). ISMAR's lagoon model generates input depth files for their canal hydrodynamics model. Prior to running the canal model, these input depth files must be obtained (Venice Project Center, 2013). They contain water levels at all boundary nodes in the model. If any of these input files are edited, then the model must recompile before running. **Figure 2.4** shows the process of executing the model. As indicated, the recommended output step for the model is 60 minutes. Also, the user will need to input whether or not they wish to run the model with a Manning Constant. If the user wishes to use the constant (by inputting *sí)*, the manning constant will vary according to each segment. If no, the Manning Constant will remain the same for all segments. (Venice Project Center, 2013).

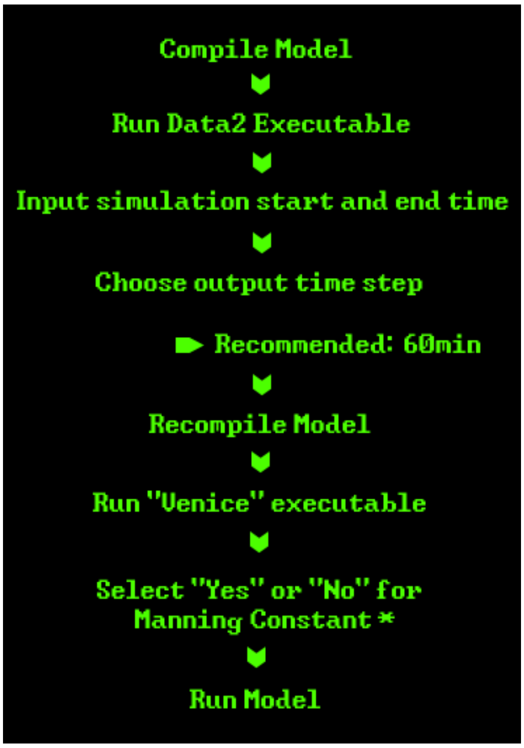


Figure 2.4. How to execute the model

Currently, ISMAR's canal model works as demonstrated in the Appendix. First, ISMAR's Acqua Alta Tower receives real-time information on tides from the Adriatic Sea to the Venetian Lagoon. Next, ISMAR runs its lagoon model to predict the water levels at 40 nodes representing entrance points from the lagoon to canals. The lagoon model's output is then used as input to the canal model to determine water levels within Venice. Before the process repeats, the lagoon and canal models provide feedback to the Acqua Alta Tower so that future forecasts may be improved.

2.5 Water Levels and Flood Prevention

The Adriatic Sea is the most influential component of sea-level and flood levels in Venice. Due to its geographical location, it has, according to Tomasin (2005), "two dominant components of the tide, M2, the semidiurnal lunar oscillation, and S2, the solar one" (p. 71-78). These astronomical tides are the main cause of *acqua alta* in Venice. Mathematical models have been developed to successfully forecast surges in tides. When government officials forecast these surges, they sound sirens about three hours in advance to warn the population. The sirens go off if they forecast tides over 110 cm, which means about 12% of the city would be flooded.

High tides are divided into three main categories: "intense - between 80 and 109 cm, "very intense - between 110 and 139 cm", and "exceptional high waters - above 140 cm." "Most recent results … show that with a tide level up to 90 cm, the city isn't affected." Whenever water levels rise over 90 cm, however, the city starts to get flooded. For example, according to recent results, 100 cm floods about 5% of the city, 120 cm floods about 29%, 140 cm floods about 55%, and 180 cm floods about 79% of the city.

To protect the Venetian population and landmarks from continuously rising water-levels, researchers and engineers have tried to find solutions for the floods. For instance, as Spinelli & Folin (2005) quote Giuseppe Bianco, 19th Century Venice's head engineer:

"..since the public pavement levels of Venice are at an average of only 80 cm above common high tides, and the exceptionally high tides have reached levels of 120 cm more than twice in 10 years, it would benefit the city to raise its public ground level surfaces by 50 cm. Moreover, the private citizens will be required to raise their ground floor levels, along with the doors and windows, of their homes."

Recently, however, it has become clear that raising the ground level is not an option anymore due to, as Spinelli & Tolin (2005) wrote "the necessity of safeguarding and conserving Venice's architectural heritage" (p. 147-154). Raising the ground level will necessitate raising door and window levels, thus compromising historical sites and access to shops and homes.

An alternative solution is the MOSE project. Plans for large-scale infrastructural renovations began in the early 1970s, but only in 1982 were consortiums legally permitted to design a system capable of protecting the city from the high tides. The MOSE (*Modulo Sperimentale Elettromeccanico* - Electromechanical Experimental Module) project was approved in 1994 and environmental studies were completed in 2002. The construction of the MOSE started in 2003. The project was designed to separate the Venetian Lagoon from the Adriatic Sea by installing 78 flood gates at the three water inlets (Chioggia, Malamocco, and Lido) between the Adriatic Sea and the Venetian Lagoon. These gates will rise whenever the water level is higher than 109 cm, which is the limit for intense tides. By late August 2014, over 85% of the project had been completed. The MOSE project is expected to finish by 2017 (MOSE Venezia, n.d.).

2.6 Flood Protection and Pedestrian Mobility

The Venetian government has taken extra initiatives to ensure the safety of its pedestrians and public transport systems. In 1980, *il Centro Previsioni e Segnalazioni Maree*, (*il Centro Maree*) was created to generate an alternative pedestrian system during cases of high tides (Bon, 2014). *Il Centro Maree* would reorganize the use of their *passerelle,* or walkways, to improve pedestrian mobility during high tides of up to 120cm. When the flood sirens sound, "a team of 100 workers [rush] out and set [the *passerelle*] up so tourists and residents can mince their way around town above water" (Hale, 2003).

On the other hand, this does not completely solve the problem of pedestrian mobility. If one wishes to stray from the [walkways], they must “pick [their] path carefully, or decide to sit somewhere dry for an hour or two” (“Acqua Alta: High Water and Floods,” n.d). When the tides surpass 120cm, “the wooden walkways...begin to float.” If the high tides increase to over 130cm, although they rarely do, “most of the city’s thoroughfares [will be] underwater.” Even for high tides less than 120cm, pedestrian mobility is limited to areas where these *passerelle* are accessible. To create a more efficient solution for the pedestrian system, the Venetian government needed to gather the most up-to-date data with regards to the city’s pavement elevations. A study of the altimetry of the island’s major pathways was conducted by Canestrelli, Faccinelli, and Miglioli (1983) to help with alternative pedestrian routing for flooding. In recent years, Insula SpA, an urban maintenance division of the City of Venice, conducted altimetry measurements throughout the island and compiled their data into a geographical information system (gis) project called RAMSES (*Rilievo Altimetrico, Modellazione Spaziale E Scansione 3D*). According to reports from Insula (2011), the outcomes of this project were three-dimensional representations of the pedestrian infrastructure based on Insula’s surveying data.

2.7 Tidal Latency

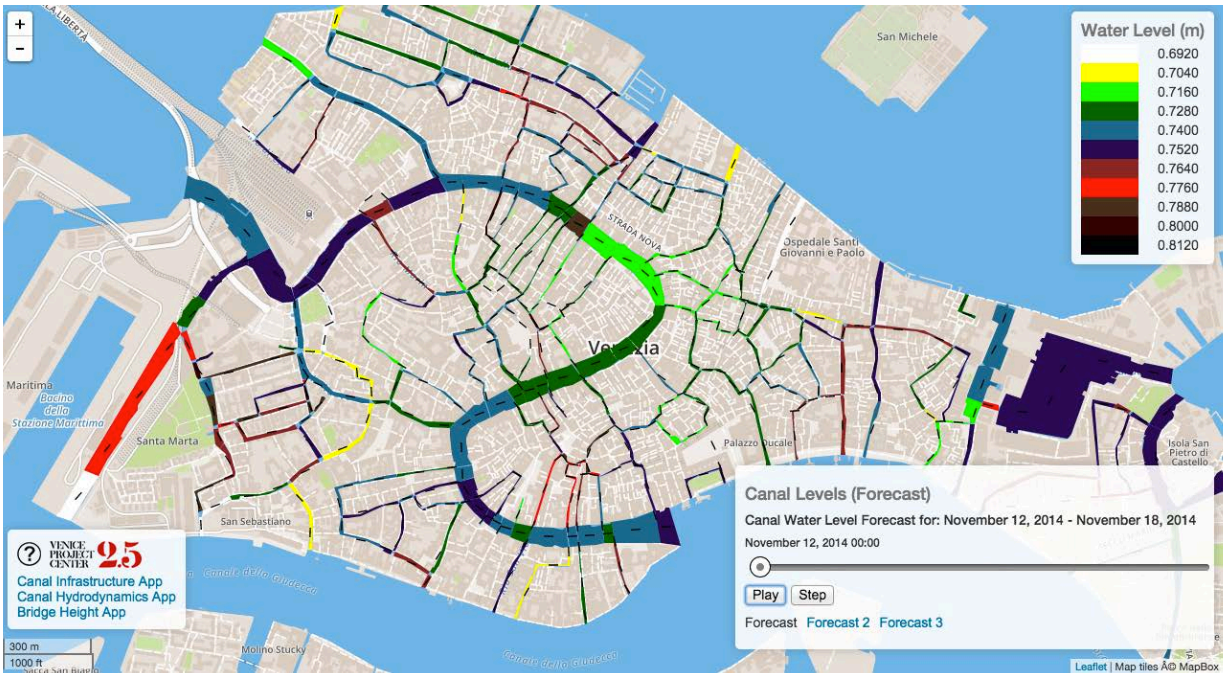
When talking about tides within the islands of Venice, it is important to keep in mind that, although *Il Centro Maree* provides the tide level at *Punta Salute*, not all of the canals will have that same level. The time it takes for the water to spread throughout the canals is called Tidal Latency. When the water comes into the Venetian Lagoon from the Adriatic Sea, it starts filling up some canals before others, until it reaches a peak, in which all of the canals will have the same water level. After this peak, water will start going out of the canals of Venice. Like with the incoming tide, some canals will have their level lowered before others, until it reaches a trough, in which all of the canals will, once again, have the same water level. In order to design our mobile web app, which will be discussed in depth in **Section 5.0**, we needed to understand how the incoming and outgoing tides behave.

2.7.1 Water Level Application

In order to better understand how the rise and drop of the tides work in the canals of Venice, we created a visualization for analyzing the water level behavior. The visualization shows the different water levels at different places in the Venetian canals using information acquired from the hydrodynamics model.

When designing the web application, a very important factor that we had to keep in mind was that as the tide rises and drops, the water level is not the same everywhere within the islands, since it takes time for the water to spread throughout the canals. As previously mentioned, the current tide mobile apps created for Venice do not take this into account, but rather assume that the level in all of the canals will always be the same as *Punta Salute*. In order to better analyze the time offsets between *Punta Salute* and the other canals, a color map is ideal. As previously mentioned in **Section 2.4**, ISMAR provided us with information that they acquired from their lagoon model. The file they sent us gave the information at the forty different points where the canals intersect the lagoon. We used this file as the input file for the hydrodynamics model. When we ran the hydrodynamics model with the forecast, we got, among other types of data, water level for 505 different canal segments within the islands of Venice. We created a visualization that shows the difference in water levels for each of these 505 segments.

We chose a file from ISMAR, ran it as the input file for the hydrodynamics model and got a file as output with various values for each canal segment. Then, we used a program provided to us by the 2013 Canals IQP group. We changed the program to output a file with water levels instead of water velocities. With this new water levels file, we were able to construct the visualization based on the Canals Hydrodynamics Model.



Canal Levels (Forecast)

Canal Water Level Forecast for: November 12, 2014 - November 18, 2014

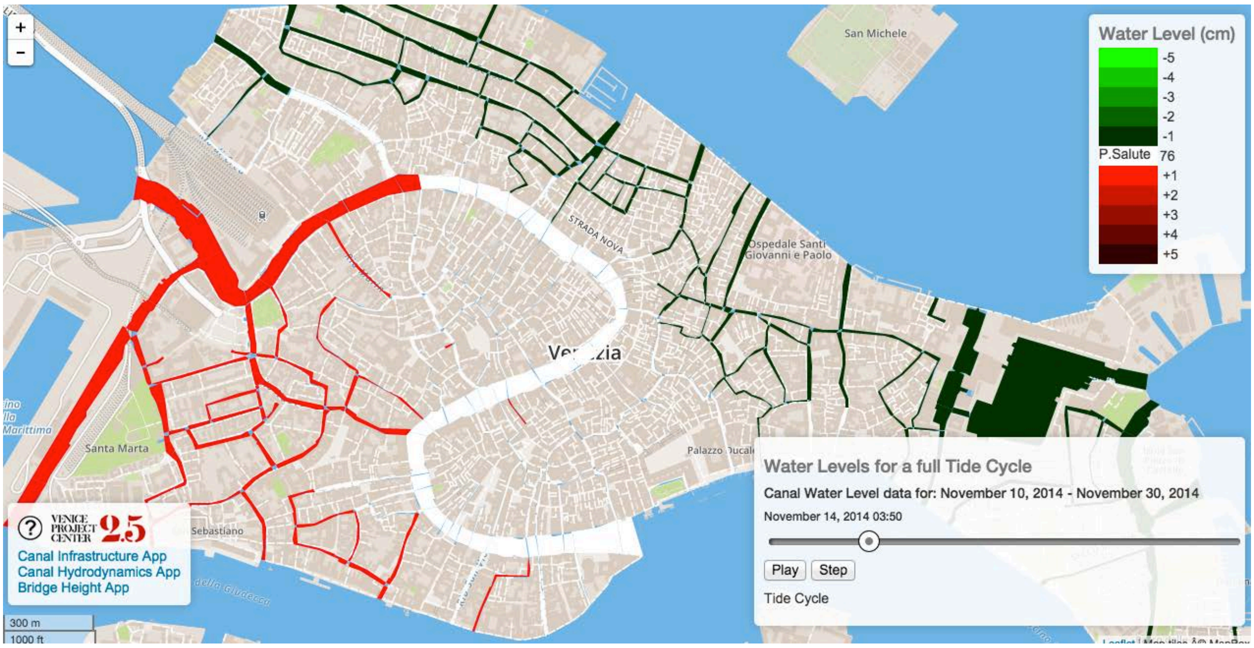
November 12, 2014 00:00

Figure 2.5. Water Level App

The difference between the lowest water level and the highest water level is very small, in the case of **Figure 2.5** it is about 12cm. Therefore, to make the gradient more effective, we change the levels respective to each color every step. For every step, we find the lowest and highest level in the canals and determine the other values based on those. By doing that, we make sure that the precision will be high enough so that the gradient effectively shows the difference in each segment. This is a great asset for the development of the web application, since the main difference between the new web application and the currently-existing ones is that it will use this time offset to create a higher forecast precision.

2.7.2 Water Level Delta Application

Expanding on the studies of how the incoming and outgoing tide behaves within the islands of Venice and how it spreads throughout the canals, we developed another visualization. This visualization uses as input past data from a full tide cycle. The visualization starts on November 10, 2014 and goes until November 30, 2014. Unlike the previous application, which shows the water level in each of the 505 canal segments in Venice, the Water Level Delta Application shows the difference in water level as compared to the level at *Punta Salute*.



Water Levels for a full Tide Cycle

Canal Water Level data for: November 10, 2014 - November 30, 2014

November 14, 2014 03:50

Tide Cycle

Figure 2.6. Water Level Delta App

Once again, we acquired the necessary data for the visualization from ISMAR's Lagoon Model and Canal Hydrodynamics Model. ISMAR ran both models using the past data for the required time interval. We extracted the water levels from the output of the models and were able to determine the water level for the 505 different segments. Using this information, we were able to compare each of the water levels to the value of *Punta Salute* and visualize the behavior of the tides.

As it is possible to see from **Figure 2.6**, the value registered by *Punta Salute* is always white and in the middle of the map key. The value for *Punta Salute* varies on each step based on the real past value from that day and time. Thanks to the model's outputs, we also get the water levels in the remaining 504 canal segments. From that information, we compare each of these values and we are able to determine how the water spreads within the island. For example, **Figure 2.6** shows that, for November 14, 2014 at 3:50am, the canals in the center and lower middle section of Venice have the same value as registered by the sensor at *Punta Salute* (76 cm). In contrast, the canals in the eastern and northern parts of Venice all have water lower than *Punta Salute* and the canals in the western part of the city all have water level values higher than the one registered by *Punta Salute*. From this information, we are able to see how the water is coming into the islands of Venice.

These visualizations are great assets for the development of the web application, since, as will be discussed in **Section 5.0**, one of the main differences between our new web application and the current ones is that it will use this time offset to create a higher forecast precision.

Based on this water level comparison between *Punta Salute* and the other canals in Venice, our group was able to create generic maps that demonstrates tidal latency by colors for both spring and neap tide. The 10 maps can be found in **Appendix C.**

3.0 Validating Tidal Latencies

The team used a tide sensor, *Cleverpole*, to validate tidal latencies. *Cleverpole* is a device provided by Eraclit Venier, SpA to measure tide levels in real-time. As seen in **Figure 3.1**, the *Cleverpole* consisted of a two meter long PVC pipe, a white datalogger box, a battery, and the sensor circuit. The sensor was installed in different regions of Venice and served as our most important instrument. Even though it has only one application - to measure tide levels - the information provided by the sensor has proven to be useful to compare with other sources of data including: *il Centro Maree*'s updates on *Punta Salute*, ISMAR's model, and even our own manual measurements.

Figure 3.1. Cleverpole installed at Campo de le Gorne

ISMAR's model and *il Centro Maree*'s forecasts are all based on mathematical probability tools to predict future tide levels. While *Centro Maree* only forecasts levels for Punta Salute, ISMAR's model calculates levels for water levels at 505 different canal segments. Even though ISMAR's finite element method-tool is very powerful and takes into account many physical and meteorological components, calculations from the model become increasingly more complex as they go further from the edges of Venice.

The purpose of the sensor is to calibrate and validate the points calculated by ISMAR's tool. It will also serve to compare the time differences between the tidal cycles between the location of the sensor and *Punta Salute*. These measurements help us understand more about the behavior of tides, which consequently helps us develop a more precise logic for the development of our web app.

3.1 Sensor Output

Perhaps the most important part of the research involved in this project is how we work with and understand the data output from the sensor. This data will give us an accurate representation of the tide for the region where the sensor is installed.

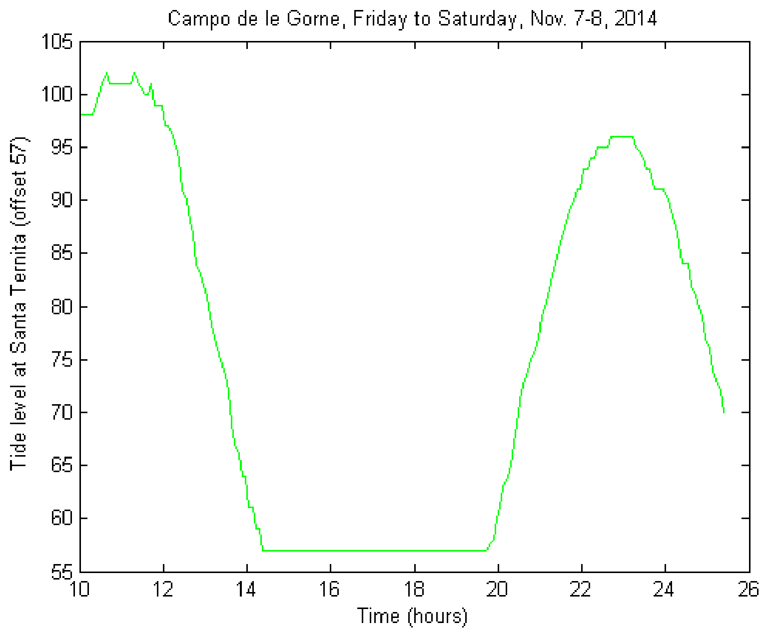
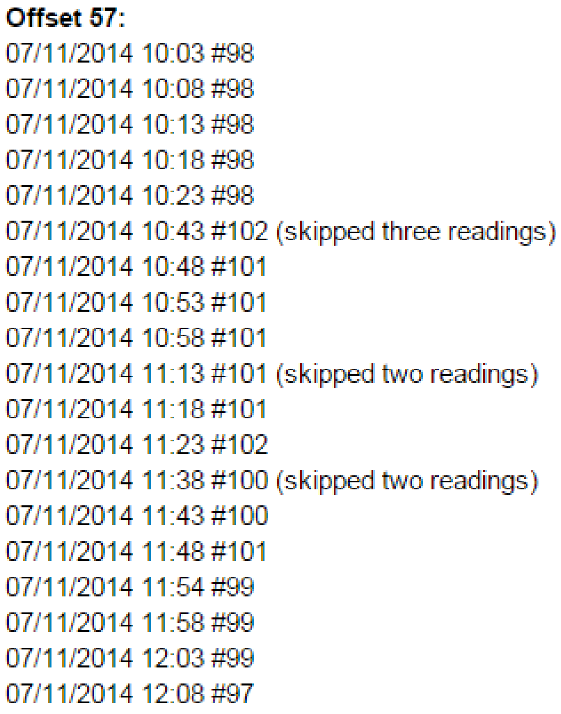


Figure 3.2. Sensor output during spring tide

Each email sent by the Cleverpole sensor includes date and time information as well as calibration information for the sensor. The computer program provided by Eraclit reads this calibration information and automatically sends the height information with the time stamp. Since emails are sent every five minutes, the resolution is 'low', but, as seen in **Figure 3.2**, the sensor outputs a sinusoidal curve for a full cycle. Notice that between 14 hours and 20 hours of Nov. 7 there is a straight line that measures 57cm. This means that the tide was less than 57cm, but the sensor cannot measure it because its 'zero mark' - the point at which the sensor starts to take measurements - is 57cm centimeters above the water. The 'zero mark' offset is fully explained in the **Appendix B**.



Offset 57:
07/11/2014 10:03 #98
07/11/2014 10:08 #98
07/11/2014 10:13 #98
07/11/2014 10:18 #98
07/11/2014 10:23 #98
07/11/2014 10:43 #102 (skipped three readings)
07/11/2014 10:48 #101
07/11/2014 10:53 #101
07/11/2014 10:58 #101
07/11/2014 11:13 #101 (skipped two readings)
07/11/2014 11:18 #101
07/11/2014 11:23 #102
07/11/2014 11:38 #100 (skipped two readings)
07/11/2014 11:43 #100
07/11/2014 11:48 #101
07/11/2014 11:54 #99
07/11/2014 11:58 #99
07/11/2014 12:03 #99
07/11/2014 12:08 #97

Figure 3.3. Sensor output during a spring tide at Campo de le Gorne

Figure 3.3 shows the sensor output for a portion of the time frame from the **Figure 3.2** above.

3.2 Faults and Errors

The sensor, as any electronic device, is susceptible to human error or subject to electronic faults. Indeed, our measurements suffered from incorrect readings from the sensor due to a sensor misaligned or because someone had turned it off. Also, cellular data coverage is not ideal everywhere. This caused the sensor to skip readings or not send emails on occasion.

These malfunctions were all taken into account when collecting the data such that only the most accurate sources were used for project purposes.

3.3 Comparing Sensor, Model, and *Il Centro Maree* Data

The most significant constituent of the web app that gives it an edge over other apps are the calculations for tidal latencies. These calculations are automatically done by ISMAR’s model, which calculates values for 505 segments around Venice. These values already take into account tidal latencies, which were explained in the background sections, as part of the frictional calculations of canals and calculations derived from the movement of tides. A different source for calculations is done in real-time with the measurements done by the sensor and *Centro Maree* at *Punta Salute*. These two different sources of data are compared to determine local time offsets.

3.3.1 Sensor Installation Locations

The map shown in **Figure 3.4** shows the locations where the sensor was installed as well as the location of *Punta Salute*. In order to acquire the most accurate information about tidal latencies, the sensor was installed in these different locations according to the lunar phase. The sensor was installed three times at *Campo de le Gorne*, at *Santa Ternita*, and twice at *Fondamenta San Severo*, which are easternmost locations on the map. The first installation at *Santa Ternita* was done for training reasons and to evaluate our manual measurements. The other two installations for both *Santa Ternita* and *Fondamenta San Severo* were done for the two different tides, neap tide and spring tide, because their behavior relative to time offset varies. The installations at *Fondamenta Nani* and *Fondamenta San Felice* were done on opposing tides. We installed the sensor at *Fondamenta Nani* for the neap time measurement and at *Fondamenta San Felice* for the spring tide measurement.

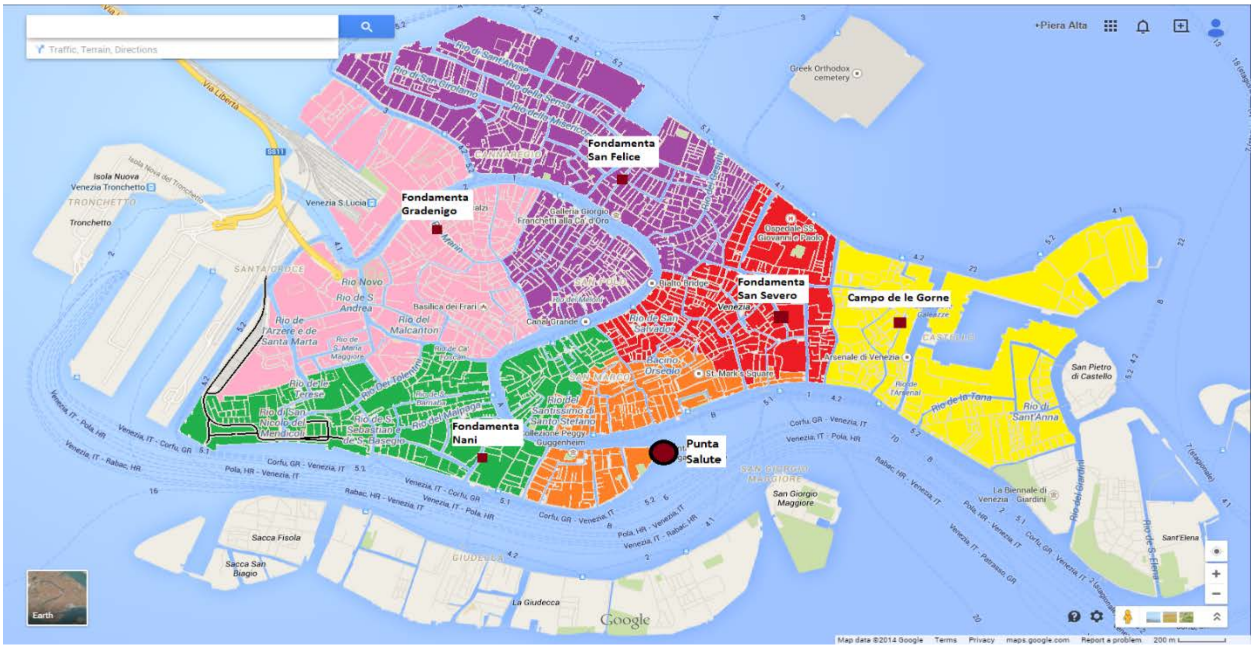


Figure 3.4. Sensor installation locations

3.3.2 Sensor Data vs. *Punta Salute*

The plots in this section were produced by taking the output from the sensor and plotting them next to information provided under Venice Project Center's Dashboard widget. The widget supplies a log of the information such as the one shown in **Figure 3.6**. It is clear that measurements at *Punta Salute*, compared to the ones from the sensor (see **Figure 3.5**) are more precise because they do not skip measurements. It is also clear from the plot of *Fondamenta San Felice*, **Figure 3.7** that there is a time offset between the two parts of Venice. Yet, it is not so clear to see these tidal latencies when examining the graph that opens this section, **Figure 3.5**. Thus, these two sets were used to evaluate the offsets. These offsets were calculated manually from both the data points and the plots. The plots helped us figure out the best instances to take the manual calculations for tidal latencies, while the data points gave us the information to calculate those points. All of the calculations are on the **Table 3.1**.

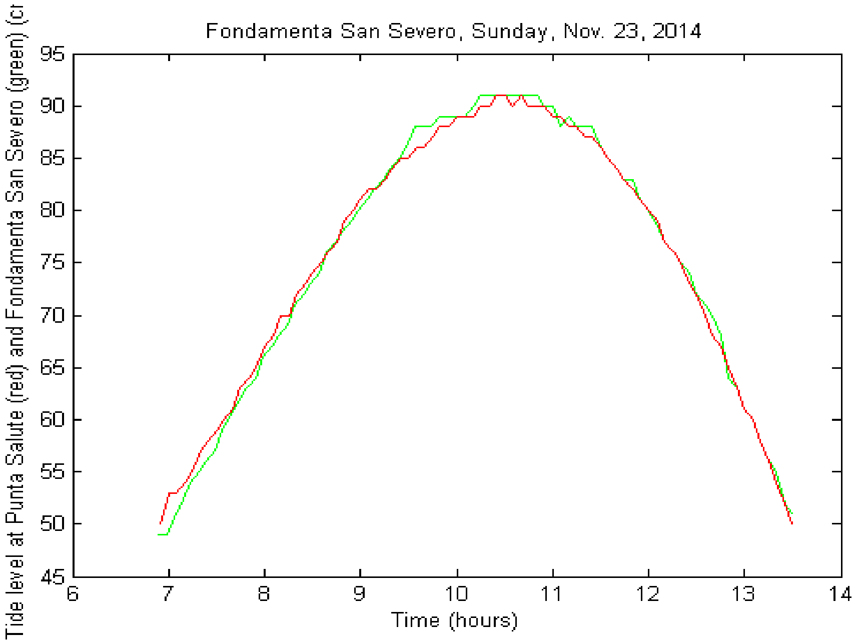
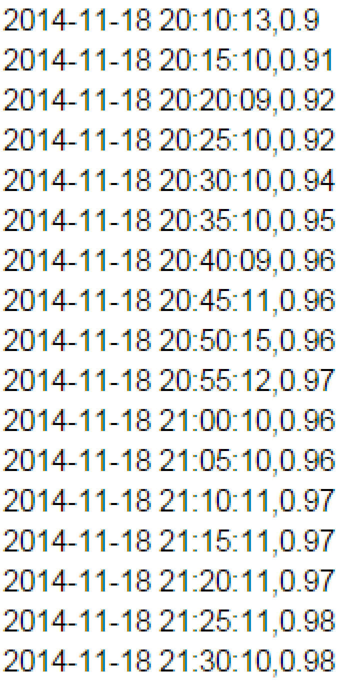


Figure 3.5. San Severo vs. Punta Salute

Figure 3.8 shows the process for the calculation of the tidal latencies. This graph shows the neap tide cycle at *Fondamenta San Severo* for a tidal peak. The three circles show which points were used for the calculation of the offset. The first circle clearly shows how instants after a change at tide level in *Fondamenta San Severo* the same change occurs at *Punta Salute*. The slope for those two segments is the same and, therefore, the two points that constitute each of the segments are used for one measurement of the tidal latency. Next, notice how the second circle has two peak values. Since the green plot does not change in value like the red plot, the first red peak is considered a glitch, while the change in green plot is followed by a similar change in the red plot. Those points are used as a second measurement for the latency. Finally, notice the 'v' shaped portions in the third circle. Those indicate that it is a good point to take a measurement because changes in the tide are corresponded. Since the first segments, that is for both colors, of the 'v' shapes have the same slope, they are also used for the measurement of the tide time offset. The average of these three measurements determines the tidal latency for *Fondamenta San Severo* for the neap tide.



```
2014-11-18 20:10:13,0.9
2014-11-18 20:15:10,0.91
2014-11-18 20:20:09,0.92
2014-11-18 20:25:10,0.92
2014-11-18 20:30:10,0.94
2014-11-18 20:35:10,0.95
2014-11-18 20:40:09,0.96
2014-11-18 20:45:11,0.96
2014-11-18 20:50:15,0.96
2014-11-18 20:55:12,0.97
2014-11-18 21:00:10,0.96
2014-11-18 21:05:10,0.96
2014-11-18 21:10:11,0.97
2014-11-18 21:15:11,0.97
2014-11-18 21:20:11,0.97
2014-11-18 21:25:11,0.98
2014-11-18 21:30:10,0.98
```

Figure 3.6. Sensor Log

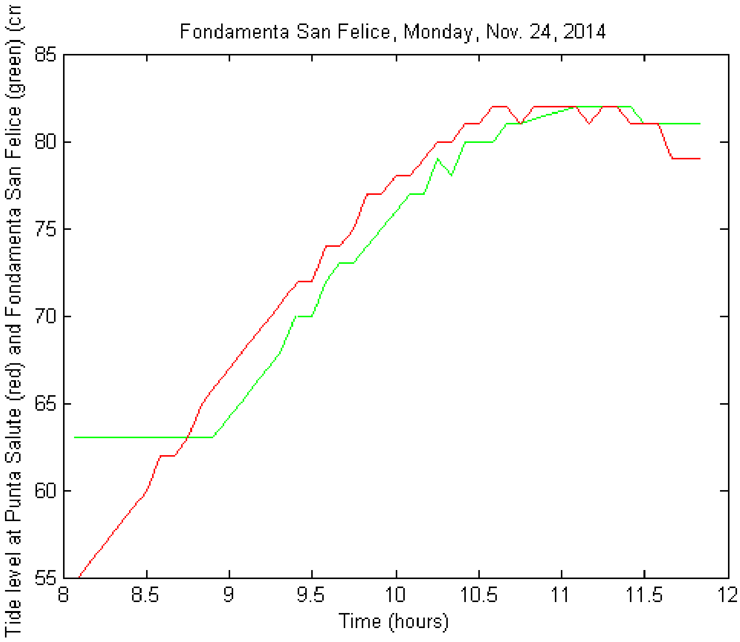


Figure 3.7. San Felice vs. Punta Salute

Table 3.1 shows the tidal latencies relative to *Centro Maree*'s measurements of *Punta Salute*. The locations can be found in **Figure 3.4**. Some of the offsets have a negative value, which means that the tidal cycle at *Punta Salute* precedes the cycle at the location. Likewise, if the value is positive, the location at which the sensor was installed, for instance *Campo de le Gorne*, precedes *Punta Salute*'s tidal cycle.

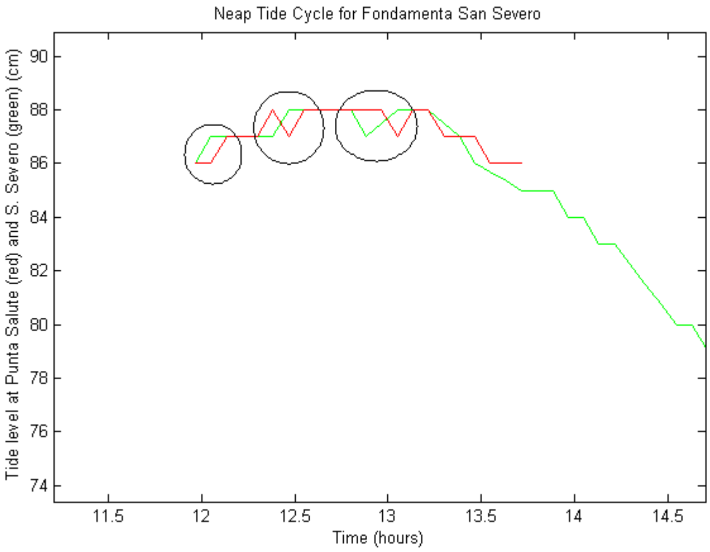


Figure 3.8. Neap tide cycle for Fondamenta San Severo

Table 3.1. Average tidal latencies for sensor locations

Location	Tidal Phase & Date	Tidal latency (average)
Campo de le Gorne	Neap, Nov. 15, 2014	-14.83 min
Campo de le Gorne	Spring, Nov. 22, 2014	-0.33 min
Fondamenta San Severo	Neap, Nov.14, 2014	5.17 min
Fondamenta San Severo	Spring, Nov. 23, 2014	0.5 min
Fondamenta Nani	Neap, Nov. 16, 2014	1.00 min
Fondamenta San Felice	Spring, Nov. 24, 2014	-11.33 min
Fondamenta Gradenigo	Spring, Dec. 9, 2014	-3.00 min

3.3.3 Model Forecasts

The third source of data is provided by the model from ISMAR. Since the model outputs daily forecasts, these values are close but don't perfectly model the tidal cycle. The model outputs precise values for 505 canal segments. This precision makes the model an indispensable tool for calculations of tidal latencies. Thus, it is important to calibrate the model with the other tools (the sensor and *Centro Maree*'s *Punta Salute*) that we already have.

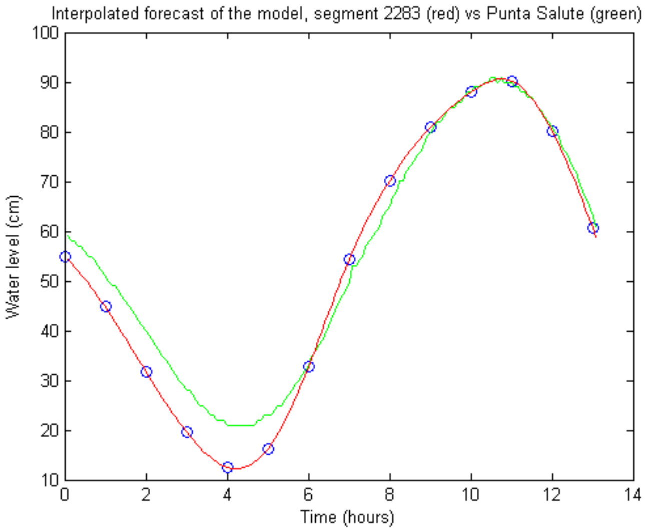


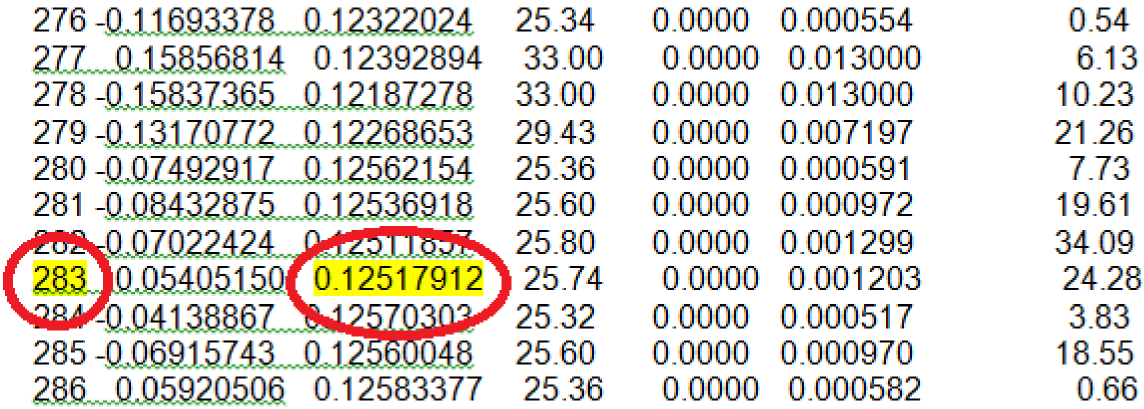
Figure 3.9. Interpolated forecast of the model

In order to calibrate the model, one must first identify which of the 505 segments corresponds to the segment at which the measurements from *Centro Maree* or the sensor. **Table 3.2** correlates the identity numbers from the model output to these locations. Once these index numbers are determined, one can check the list of output values from the model and compare it to the other sources of data.

Figure 3.9 shows the model forecast for segment 2283 (*Punta Salute*), even though it only identifies the segment as 283. The third column refers to the water level in meters. Since this screenshot was taken from the model output file for Nov. 23, 2014, the third column includes all of water levels for 505 segments at 4:00am on that same day. The other columns include water velocity, pressure and other factors that affect tides, but are not considered in this project.

Once the desired values, such as the one shown above, were collected from the model, these points were graphically compared to the data from *Centro Maree* and the sensor. Since the model only forecasts for every hour we needed to apply a mathematical algorithm, called spline, to cubically interpolate between these points to create a smooth forecast for the model. These are not enough points to determine the behavior of tides, for a tidal cycle, from peak to peak, ranges from 12 hours to 13 hours. A mathematical algorithm, called spline, was used to cubically interpolate between these points and create a smooth forecast for the model.

The following image (**Figure 3.10**) shows the real-time outputs from *Punta Salute* on Nov. 23 in green. The circles in blue represent the forecast from the model for the given hour. In red, the spline method was applied to the values in the blue circles. As it can be seen, at points the forecast will 'perfectly' model the behavior of the tide for that canal segment, while at other times the forecast will significantly diverge from the correct real-time information. In this case the largest difference between the two curves was 9.27 cm. Thus, a calibration method is very important for the accuracy of the app. This is further discussed in the **Chapter 5.0**.



```
276 -0.11693378  0.12322024   25.34    0.0000  0.000554          0.54
277  0.15856814  0.12392894   33.00    0.0000  0.013000          6.13
278 -0.15837365  0.12187278   33.00    0.0000  0.013000         10.23
279 -0.13170772  0.12268653   29.43    0.0000  0.007197         21.26
280 -0.07492917  0.12562154   25.36    0.0000  0.000591          7.73
281 -0.08432875  0.12536918   25.60    0.0000  0.000972         19.61
282 -0.07022424  0.12511857   25.80    0.0000  0.001299         34.09
283  0.05405150  0.12517912   25.74    0.0000  0.001203         24.28
284 -0.04138867  0.12570303   25.32    0.0000  0.000517          3.83
285 -0.06915743  0.12560048   25.60    0.0000  0.000970         18.55
286  0.05920506  0.12583377   25.36    0.0000  0.000582          0.66
```

Figure 3.10. Canal Hydrodynamics Model output

The following plot was done similar to the previous one, but now it compares the forecasts from the model to the output of the sensor at *Campo de le Gorne* at the island of *Santa Ternita*, where the ID number from the model is 2171. This plot was created with the values from Nov. 7, 2014, during a spring tide. Note that the values for which the output of the sensor are constant are out of the reach of sensor measurement for they have gone under the 'zero-mark', refer to the **Appendix B** for more information on sensor installation and calibration.

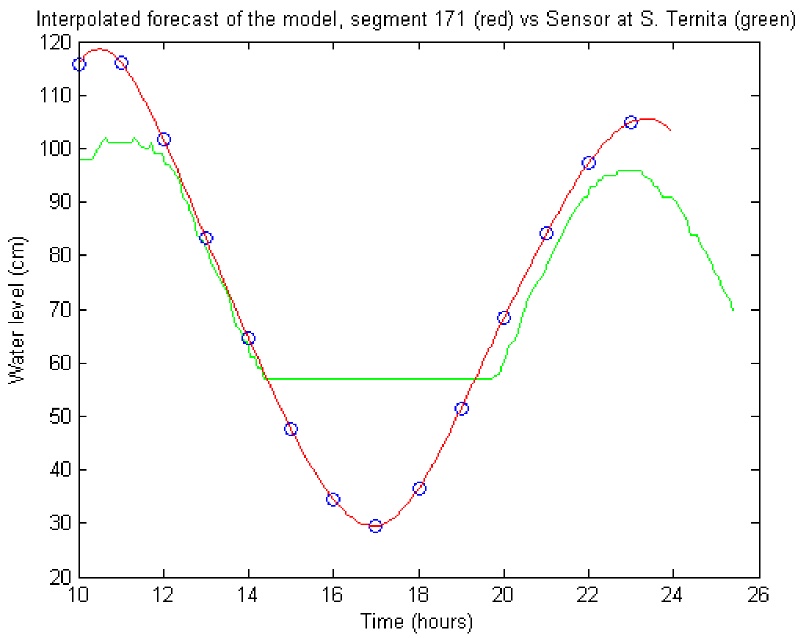


Figure 3.11. Interpolated forecast of the model

Table 3.2. Sensor installation locations

Location	Model Identification number
Campo de le Gorne	2171
Fondamenta San Severo	2151
Fondamenta Nani	2228
Fondamenta San Felice	2047
Fondamenta Gradenigo	2203
Punta Salute	2283

3.3.4 Discussion and Remarks

From the several analyses that were done as part of the research on tides, it is clear that the movement of tides through canals and the lagoon plays an important role on Venetian flooding. That is, understanding the way water spreads by mathematically modeling it is very important for the accuracy of the web app. Tidal latencies are the mathematical representation of this behavior of the water. And as it can be seen, they can largely affect the way streets flood, especially when taking into consideration the time component.

The Canals Hydrodynamics Model utilizes forecasts from the Lagoon Model, which is run by ISMAR. The model computes tidal latencies for 505 segments around the canals of Venice. The two previous plots **(Figures 3.10 and 3.11**) show that the predictions from the model are not 100% accurate, but at some parts it can model with very small error. The important question is: are the errors from the model consistent? Does the model maintain the same error margin throughout the 505 segments? It turns out from following plot that the model's outputs are consistent. The red and black curves represent the cubically interpolated values from the model for segments 2283 and 2171 (*Punta Salute* and *Campo de le Gorne*, respectively), while the green and blue curves represent the values from the model for the same segments. The fact that they are grouped together means that some mathematical formula can be applied to model outputs in order to refine the forecasting.

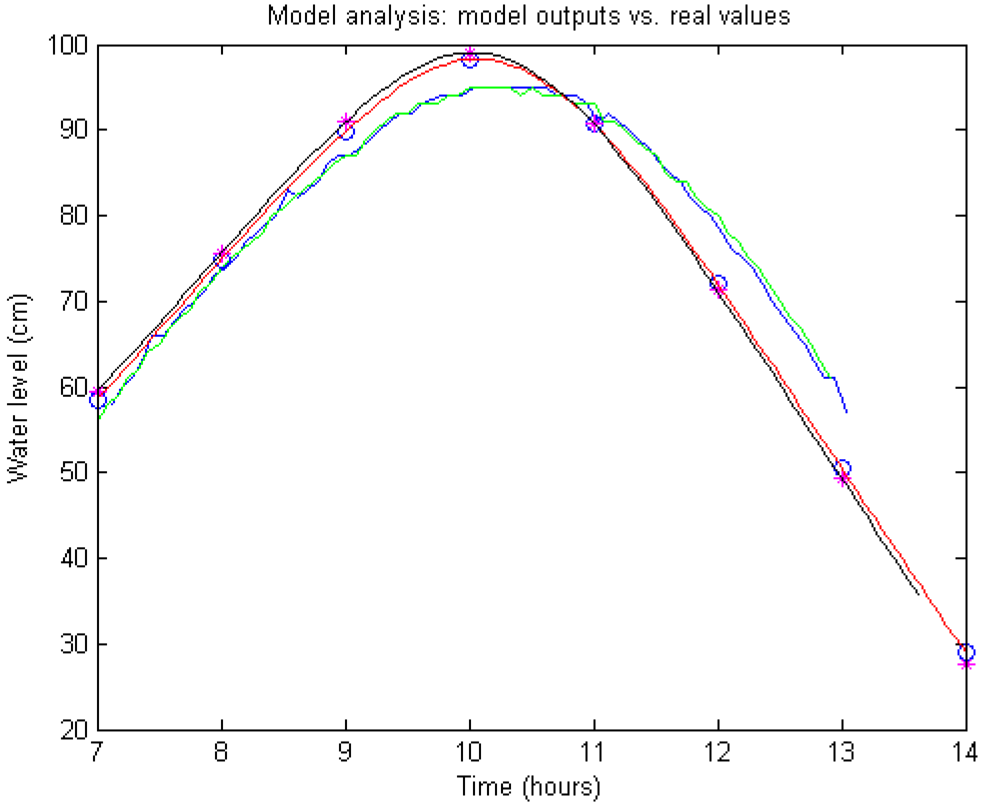


Figure 3.12. Model Analysis

Figure 3.4 shows different regions of Venice separated by their relative tidal latency. Each colored region represents a different tidal latency (the region in Orange refers to the forecast for *Punta Salute*). These tidal latencies are presented on **Table 3.1**. These regions base themselves from the locations of the sensor and were organized based on the model forecast, once the Water Levels App was completed. Finally, these values were used to validate the performance of the model and-select the model as the main source of tidal latency measurements in our web app.

4.0 Existing Mobile Applications

One way of improving pedestrian mobility during floods is through use of smartphone applications. Currently, there are several mobile applications that inform smartphone users about tide levels in the islands of Venice. There are two apps in particular that we looked at in detail. The first is *hi!tide Venice* and the second is *Water on Venice Floor*. We took a look at the pros and cons of each of these applications.

4.1 hi!Tide Venice

hi!Tide Venice is a mobile application for the current tide level as well as tide forecasts. Tide levels and forecasts are taken directly from *il Centro Maree*. This works to deliver information about how the tides are at that moment and how they are expected to change. *hi!Tide Venice* has an interesting feature that tells the altitudes of popular areas around Venice, as seen in **Figure 4.1**. The app then reports how many centimeters below or above the current tide level that area is. One issue of this application is that it does not take tide latencies into consideration. As a result of this drawback, the locations included in the points of interest may not be at the same tide level as *Punta Salute*, where *hi!Tide Venice* receives its information from. Another problem is that there is no location tracking involved in the application. Therefore, a user must be near a point of interest to know if they should expect flooding around them. Overall, *hi!Tide Venice* does well to make the *Punta Salute* values from *il Centro Maree* known, but is lacking in the sense that the flood reports are not always accurate.

PLACES 62 cm

Tide level at points of interest

Campo S. Margherita
Altitude: 120 cm Regular -58 cm

Campo S. Martino
Altitude: 120 cm Regular -58 cm

Campo S. Moisè
Altitude: 95 cm Regular -33 cm

Campo S. Pietro
Altitude: 155 cm Regular -93 cm

Campo S. Salvador
Altitude: 115 cm Regular -53 cm

Figure 4.1. hi!Tide Venice showing POIs

4.2 Water on Venice Floor

Another application, *Water on Venice Floor*, also shows current tide levels as determined by *il Centro Maree*. This application determines flooded areas of Venice and shows them on a map, with floods colored red as seen in **Figure 4.2**. This is an excellent feature, as it allows users to see where they can expect floods. During one high tide, we traveled to a supposedly flooded location. When we arrived, it was discovered that the area was not flooded at all. *Water on Venice Floor* also includes information on tides in general but does not include any tide forecasts.

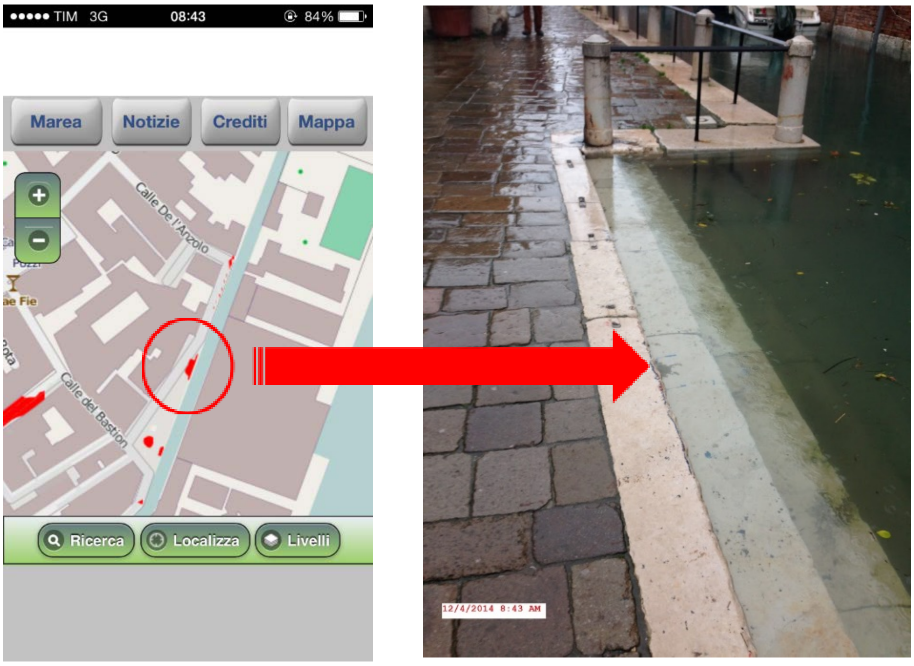


Figure 4.2. Water on Venice Floor vs. Actual Location. Reported flooding is incorrect

5.0 Designing a Better App: Piera Alta

As previously mentioned, until the MOSE project is completed, Venice is in need of new innovations to protect its population from flooding. Flooding makes moving about the city especially difficult for pedestrians. In a city where walking is the primary method of transportation, pedestrians must know the best route to their destination at any given time. Until the flooding issue is partially addressed by MOSE, there are solutions that can ease the inconvenience of moving through the city, for locals and tourists, during the varying tide levels.

After all of the data was collected and organized, we designed a mobile web application to display the gathered information to Venetian citizens and tourists. In 2013, 41% of Italians owned a smartphone. That number has grown greatly subsequently and is supposed to reach 50.9% in 2014 and 66% in 2017 (“Share of mobile phone users that use a smartphone in Italy from 2010 to 2017,” 2014). These statistics, combined with the number of tourists who own smartphones, led us to decide that the best way to distribute real-time information to both tourists and citizens would be via a smartphone web application.

The app’s main goal is to transmit all of the real-time information gathered in a user-friendly way. The application consists of two main parts: forecast and navigation. The forecast section uses the information acquired from the models available to predict that week’s tide levels. We then developed a logic to compare the water levels for the different canal segments to the pavement height data. The full extent of how we developed this logic to determine whether or not each street is flooded is discussed in **Section 5.3** of this report.

5.1 Providing Accurate Location-Specific Tide Levels

As mentioned, the existing mobile apps do not take into account tidal latency and this is one of the issues that our web app design addresses. By using the model output, we are able to determine the water level at any of the 505 canal segments at any given time: real-time or forecasts.

The application’s main screen will consist of a map of the city of Venice. It will default to the user’s current location and its surrounding areas, as seen in **Figure 5.1**. Beyond that, there will also be information on the current tide and the next high tide level. From the app’s main screen, there are three different actions: search an address, find a route unaffected by flood between two addresses, looking at flood status of streets for a future time or opening the app’s main menu.

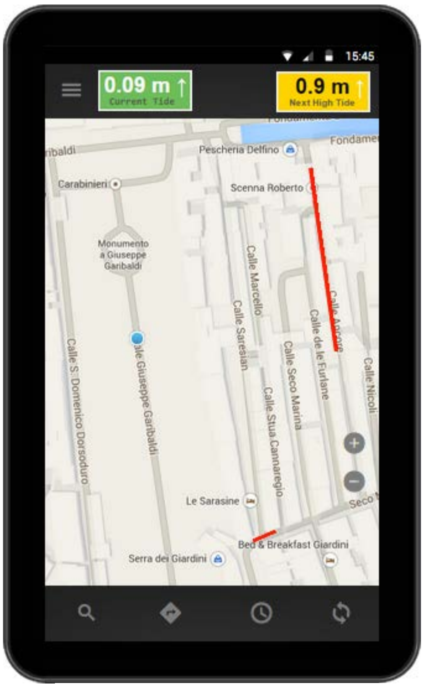


Figure 5.1. Web app main screen

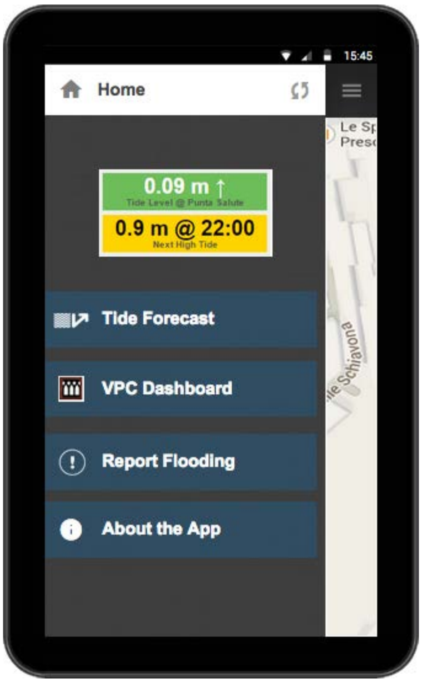


Figure 5.2. Web app main menu

By clicking on the “search” icon (the magnifying glass), the user is able to search for an address and see the flooding status of those streets. Furthermore, the user is able to click on the “directions” icon (the right arrow) and input start and end addresses. The app will then look for a route between these two addresses (if one exists) that has not been affected by floods. The other option from the main screen is reached by clicking on the “time” icon (the clock). This will allow you to choose a future time and, based on forecasts, see which streets will be flooded and which will not. The fourth and final option is opening the main menu.

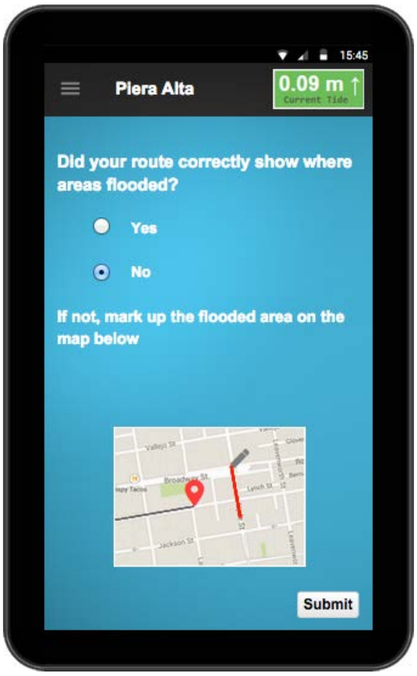
The main menu can be seen on **Figure 5.2**. It allows you to see the current tide and the direction it is going as well as the water level for the next high tide and the time which it will reach this peak. Beyond that, there are also four other buttons: “About the App”, which shows a blurb about the app, our project, and sponsors and collaborators, “VPC Dashboard”, which takes you to the existing Venice Project Center Dashboard page, “Tide Forecast”, and “Report Flooding”.

5.2 Planning Around Floods

Figure 5.4 shows our tide forecast page. This page shows you *Il Centro Maree*’s tidal forecast graph for the next 72 hours, as well as giving the user the option to plan a route. **Figure 5.5** shows that the current time is 3:45 pm. Let’s imagine that the user has an appointment at 8:45 pm and he needs to know whether or not a particular street will be flooded. The user is then able to input a particular time, in this case 8:32 pm, and from there check whether the street will be flooded or not at that time, as well as for how long it will be flooded, as also shown in **Figure 5.5**.

5.3 Incorporating Crowd-Sourced Feedback

Unfortunately, the mobile web app will not be flawless. Since a lot of the app's information is based on forecasts, any change in meteorological conditions could cause the forecast to be wrong, as discussed in **Section 5.4.3**. In order to make the app more accurate, our design includes the ability to receive feedback from users. If the app gives a particular user a route that is not affected by floods and then the user finds out that a particular street is actually flooded, the user should be able to report that discrepancy. The app would then use this information to improve the real-time information it is currently providing to the users. As can be seen in **Figure 5.3**, the team has included in the design the ability for users to accomplish just that. This means that the more users that app has, the more accurate it will be, which, in turn, will mean more users will want to use it.



Did your route correctly show where areas flooded?

○ Yes

● No

If not, mark up the flooded area on the map below

Figure 5.3. Flood report

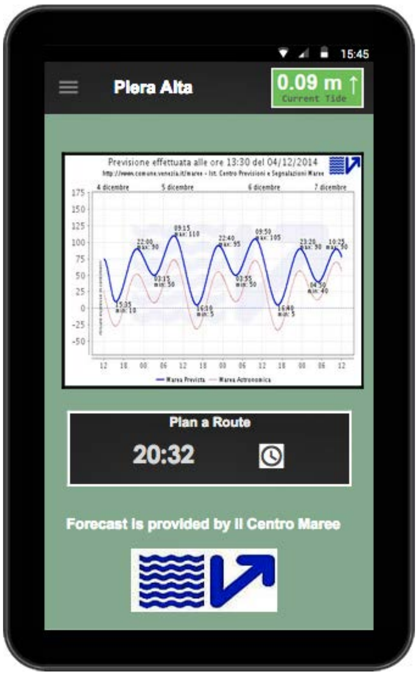


Figure 5.4. Tide Forecasts

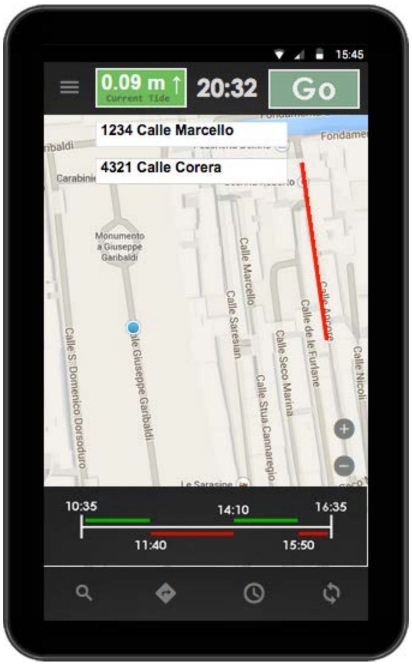


Figure 5.5. Directions for the future

This mobile application will be useful for both citizens and tourists. From their smartphones, they will be able to check the tidal forecast and adapt their daily routines accordingly. Also, if they need to travel around the islands during high tide, they can use the mapping tool to check for the best route to their desired destination. Lastly, they will be able to contribute to the app's usefulness by updating any inaccurate information.

5.4 Incorporating Floods into Web App Design

There are two major sources of water that cause flooding: edges of the islands and drains. When the water level is higher than the pavement level, water spreads through the surface of the island, flooding the regions that are lower than the tide level.

For example, some of the edges of the island of Piazza San Marco are as low as 100cm. Any tide higher than 100cm will start flooding the island from the sides. However, it is important to keep in mind that although the edges of the islands are at 100 cm, the island's lowest points are the drains, which are as low as 71cm. Since Venice is surrounded by and "above" water, whenever water is higher than the level of the drain, water starts coming up. This means that flooding does not only occur from the overflow of canals. It indicates that portions of the city that do not have any canals next to it are still susceptible to flooding due to the low altitude of the drains relative to the water.

5.4.1 Floods from Canals and Lagoon

In order to correctly understand how water flows up the surface, we utilized our test island, Santa Ternita. On November 5, 2014, the water level was forecasted to reach a peak of 115cm. We prepared for this high tide by mapping all of the regions of the island that would get flooded at this level. Our team used the GIS pavement layer in order to check all contour levels in the island whose pavement was equal or less than 115cm. Once we got to Santa Ternita, our job was simply to take measurements of the water level relative to the pavement height in order to verify our logic.

According to the GIS file that we acquired from Insula, the ground levels for one of the streets in the island, *Calle della Campare*, has pavements as low as 44cm (the steps to the canal) and surface levels going from 94cm to 124cm. If the tide reached 115cm, then some portions of this street would be as much as 21cm under water. Indeed, according to our measurements this street as well as some other portions of the island flooded. Yet, our measurements added to the pavement height consistently suggested that the tide's peak was either 111cm, instead of the original 115cm. These measurements were either equal to the ones at *Punta Salute* or differed by a low margin. Since these measurements were taken in various parts of the island - *Calle della Campare*, *Calle del Mandolin*, *Corte Soranzo*, *Campo de le Gorne*, and *Calle Celsi Castello* - our test experiments have led us to believe the way pavements floods is as we previously mentioned. Checking the water level at a canal segment against the height of the pavement bordering that canal can correctly identify which streets will flood, although this logic may not correctly identify the level of the flooding.

5.4.2 Floods from Drains

Another source of flooding is the storm drain system. Drains normally bring excess water out of streets. When water levels supercede the height of the drain, water from the system overflows onto the street and cause flooding. If the drain is situated away from canals, any nearby flooding is likely due to drain backflow as opposed to canal overflow. By accounting for the locations of storm drains, the final web application becomes more accurate in predicting areas of flooding.

5.4.3 Possible Discrepancies

Now that the physical logical for flooding has been established, it is necessary to revise the logic, check for possible errors or glitches, reevaluate it, and try to improve the precision of the app. After all, the logic developed for the web app has a number of "simplifications, assumptions or approximations" in order to make the calculations more practical and reasonable. These simplifications could end up in misalignments between the forecasted tides and flooded streets and the actual values for tides and flooded streets. Obviously, since the model by ISMAR functions based on predictions and past results, it cannot and will not be able to perfectly determine the behavior of tides. Still, as more features are included in the app, more processes are added to the algorithm (the logic of the program that runs the app). The simplifications that constitute these new features is added to other previous assumptions. Consequently, the large number of "simplifications, assumptions and approximations" can hinder the precision of the app.

One simplification in our logic, for example, is related to the way drains flood pavements. Because we do not know the conditions of the drains or of the pipes that lead water up the drains, some storm drains may not comply with our logic. As a matter of fact, when we took measurements of the water levels in Piazza San Marco, the water level coming from the drains was consistently around 100 cm, while the level registered by Punta Salute was 105 cm. This difference accounts for a precision that is not easily attainable. Yet, the app's feature that will allow users to report discrepancies, discussed in **Section 5.3**, but are in real life, will better the precision of the app and will correct these possible inconsistencies.

Due to the different meteorological factors the behavior of tides is not perfectly predictable. The model supplied by ISMAR cannot, therefore, always precisely determine the levels of tides at all 505 canal segments around the islands of Venice. A slight change in wind, for example, could cause a miscalculation in the model which, in turn, could cause the web app to incorrectly simulate floods.

6.0 Recommendations

Following completion of work on this project, we have come up with several recommendations for future groups to take into consideration. Our desire is to help those whose projects involve some study of canal hydrodynamics or tidal behavior.

6.1 Recommendations on Installing the Sensor

After countless installations of the sensor, we have come up with a few suggestions on how to both mitigate and expedite the process.

The most troublesome part of installing the sensor for us was finding a location suitable for installation. There are many QGIS files that we used that include the locations of buildings and docks/steps. These can be found by going to our website (on the title page) and following the *Files* link. Using these files, it is easy to find potential areas for installation. The group should then take a walk to these locations and inspect their viability prior to bringing the sensor there. Additionally, potential locations can be found by simply walking through the city and inspecting any places that catch an eye.

A recurring problem with installing the sensor was ensuring that it was secure and stayed straight. Most of the canal walls are rigid, with bumps and dips in the surface. This proves to be especially troublesome when attempting to use the wall as support for the sensor. One method that may be useful for future groups working with this sensor would be to attach a straight, flat object to the sensor pole - such as a plank of wood. This way, the plank of wood can rest against the outermost piece of the wall and serve to stabilize the sensor in a straight position. The sensor pole would no longer have to rely on a flat canal wall to rest upon.

6.2 Recommended Installation Locations

The most useful and easiest location that we found for the sensor was on *Campo de le Gorne* on the island of *Santa Ternita* in *Castello*. From this location, the tide levels for *Rio de le Gorne* can be monitored. This position was originally selected as a test island, but proved to be indispensable. Another useful location that we returned to often was on Fondamente San Severo in Castello. There are several sets of steps leading into Rio de San Severo that can serve as points of interest for the sensor. Any area that is not overpopulated (especially by tourists), easily accessible (steps or docks make access easier), and has a railing and/or hooks has the possibility of yielding useful results for any project that utilizes the sensor or one of a similar usefulness.

6.3 Recommendations for App Design

Since our Web App was not completed. It is important to help other teams with thoughts that could help them develop the app accurately. Further, it is also relevant to give them other suggestions that could make this app even more complete by incorporating other features, such as elevation of bridges and information about public transportation.

6.3.1 Developing the Computer Logic

There are some components and features of this web app design that have not been fully implemented due to time constraints. These components require a better organized research process for the creation of a logic that will be able to translate the physical understanding of tides and floods to a computer program that will be the platform for the web app.

For the seven weeks we worked on this project we focused on studying the behavior of tides. We moved the sensor around the islands of Venice in order to gather real-time data for tidal latencies. Yet, if we had more sensors and were able to install them on more locations, we would be able to understand even more about tidal latencies. This way, we would be able to compare other valuable pieces of data to the Canal Hydrodynamics Model. In turn, this advancement would help us develop a better mathematical logic for the web app computer program, which would avoid large forecast errors.

When starting the development process of the application, one of the primordial things to achieve is finding a way to tie together the water levels provided by ISMAR's model and the pavement data provided by Insula SpA. Due to time constraints we were not able to get as far as starting to develop this logic. The pavement data include isolines of pavement heights and the model data are just the water values for each segment. In order to determine which streets flood or not, it is necessary to check the water level for each of the 505 segments and compare them to the isolines that are in contact with that segment. If the water level is higher than the value for the pavement, that street would flood. It is not a simple thing to do, because in order to figure out which segment is next to which isolines, the group would need to find a way to relate the segment IDs and the isoline IDs (which follow no particular order). Therefore, we believe that the best way to compare these two would be by using their GPS coordinates found in the GIS layers from ISMAR and Insula. After this has been done, the foundation for the most important feature of our web app will be ready for development.

Other ideas for future enhancements of the web app will be found by the future developers of the web app. Thus, it is important to organize the web app into structure that can continuously be developed by future groups.

6.3.2 Other suggestions

After presenting our application design, we were given a couple of suggestions from actual Venetians on features that could be included.

The first suggestion was regarding the *passerelle*. If a street or square is flooded but has *passerelle* set up, the application should not show this area as being flooded. Instead, the map should include these walkways and how far they extend into the street or square. This way, pedestrians would know that although the area may be flooded, they will still be able to walk through without walking into the water.

The second suggestion concerns the public transportation system and personal vehicles. When *acqua alta* occurs, there is the possibility that boats will not be able to pass underneath bridges. The final application design should incorporate the application found on bridges.veniceprojectcenter.org. With this new feature, users of the Piera Alta app will be able to plan boat routes along with walking routes.

6.4 Additional Recommendations

One event that, while not interfering with our work, proved to be bothersome was those that questioned what we were doing when installing the sensor. Most were simply interested in what our sensor was, but a few held concerns and were irritated by our presence. We recommend that future project groups obtain a letter of permission, written in Italian and signed, from either ISMAR or *il Centro Maree*. In most cases, the people interacting with us spoke little or no English. This would sometimes render our attempts to adequately explain our project fruitless. We recommend that a letter of permission is obtained prior to, or immediately after, arriving in Venice. This will serve as a means of explaining the project to curious or concerned citizens as well as proving that the proper permissions have been obtained by the group.

Furthermore, future groups that will focus on tidal behavior should invest time into learning about tides, preferably while working on the PQP stage. Understanding how tides work and what causes them will be valuable to future groups in preparation for IQP. Furthermore, we recommend that future project members pay attention to the lunar phases as these have their specific effects on the tides and define important times to study and monitor the tides.

Bibliography

Acqua alta: High water and floods. (n.d.). Retrieved October 16, 2014, from http://www.italyheaven.co.uk/veneto/venice/acqua-alta.html

Amilcar, M., Bourgeois, A., Setalsingh, S., & Tassinari, M. (2010). Mobility in the Floating City: A Study of Pedestrian Transportation. *Venice Project Center*. Retrieved from WPI Research Guides.

Ammerman, A. (2005). *The Third Dimension in Venice* (pp. 107-115). New York: Cambridge University Press.

Bon, E. (Ed.). (2014, September 19). Comune.venezia.it - City of Venice - Home - City of Venice ... Retrieved October 15, 2014, from http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1

Bossalini, D., Gardner, B., Mathews, T., Wills, M. (2013). Canals, Bridges and Urban Maintenance. *Venice Project Center*. Retrieved from WPI Research Guides.

Bramblett, R. (2013, May). Reid’s Italy. Retrieved from http://www.reidsitaly.com/destinations/veneto/venice/planning/around_by_foot.html

Breil, M., Gambarelli, G., & Nunes, P. (2005). Economic valuation of on-site material damages of high water on economic activities based in the city of Venice: results from a dose response expert-based valuation approach. In *Flooding and Environmental Challenges for Venice and its Lagoon*. New York: Cambridge University Press.

Canestrelli P., Facchinelli F. e Miglioli M., (1983), Profili altimetrici in Venezia e isole per la viabilità pedonale in caso di "acqua alta", non pubblicato, Comune di Venezia - CPSM

Caniato, G. (2005). *Between Salt and Fresh Waters*. New York: Cambridge University Press.

Cavaleri, L. (2014). The oceanographic tower Acqua Alta - activity and prediction of sea states at Venice. In *Coastal Engineering* (1st ed., Vol. 39, pp. 29-70). Elsevier.

Chappell, U. (Ed.). (n.d.). Retrieved October 16, 2014, from www.milanworldsfair.com

English Version. (n.d.). Retrieved from http://www.acqualta.org/about-english

Hale, E. (Ed.). (2003, March 5). Can Venice Be Saved? Retrieved October 16, 2014, from http://usatoday30.usatoday.com/travel/news/2003/2003-03-05-venice.htm

Kable Intelligence Limited. (n.d.). Retrieved December 17, 2014 from: http://www.water-technology.net/projects/mose-project/

Kington, T. (11, November 12). Venice 'high water' floods 70% of city. Retrieved October 16, 2014, from http://www.theguardian.com/world/2012/nov/11/venice-floods-high-water-italy

La Marea di Venezia [Photograph]. (2014, November 12). Retrieved November 23, 2014, from http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1748

Mack, B. (2012, September 11). Tourism overwhelms vanishing Venice. Retrieved from http://www.dw.de/tourism-overwhelms-vanishing-venice/a-16364608

Meteorological Effects on Tides (n.d.). Australian Government Bureau of Meteorology.

Retrieved from: http://www.bom.gov.au/oceanography/tides/met_effects.shtmlNational

Ocean Service (2008, March 25). National Oceanic and Atmospheric Administration. Retrieved November 22, 2014, from: http://oceanservice.noaa.gov/education/kits/tides/tides06_variations.html

QHyseni (Author). (2012). *Fazat e Hënës* [Diagram]. Retrieved November 22, 2014, from: http://commons.wikimedia.org/wiki/File:Fazat_e_H%C3%ABn%C3%ABs.jpg

Ramses: A project for the preservation and protection of Venice. (2011, June 15). Retrieved October 16, 2014, from Ramses: a project for the preservation and protection of Venice

Share of mobile phone users that use a smartphone in Italy from 2010 to 2017. (2014, January 1). Retrieved October 16, 2014, from http://www.dw.de/tourism-overwhelms-vanishing-venice/a-16364608

Sood, S. (2011). Keeping Venice from Sinking. British Broadcasting Channel. Retrieved December 17, 2014, from http://www.bbc.com/travel/feature/20110225-travelwise-keeping-venice-from-sinking

Spinelli, M., & Folin, M. (2005). Local flood protection measures in Venice. In *Flooding and Environmental Challenges for Venice and its Lagoon* (pp. 147-154). New York: Cambridge University Press.

Station installed in Malamocco Port [Photograph]. (n.d.). Retrieved November 22, 2014, from: http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1705

Stazione di Punta Salute Grand Canal [Photograph]. (n.d.). Retrieved November 22, 2014, from http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1674

Tomasin, A. (2005). Forecasting the water level in Venice: Physical background and perspectives. In *Flooding and Environmental Challenges for Venice and its Lagoon* (pp. 71-78). New York: Cambridge University Press.

Umgiesser, G. (2004). A finite element model for the Venice Lagoon. Development, set up, calibration and validation. In *Journal of Marine Systems* (1-4 ed., Vol. 51, pp. 123-145). Elsevier.

Yildez, H. (2003). Estimates of vertical land motion along the southwestern coasts of Turkey from coastal altimetry and tide gauge data. In *Advances in Space Research* (8th ed., Vol. 51, pp. 1572-1580). Elsevier.

(n.d.). Retrieved from https://sites.google.com/site/shyfem/

(n.d.). Retrieved October 16, 2014, from https://www.mosevenezia.eu/

(2013, January 1). Retrieved from http://canals.veniceprojectcenter.org/hydro/

Appendix A – Model Graphics

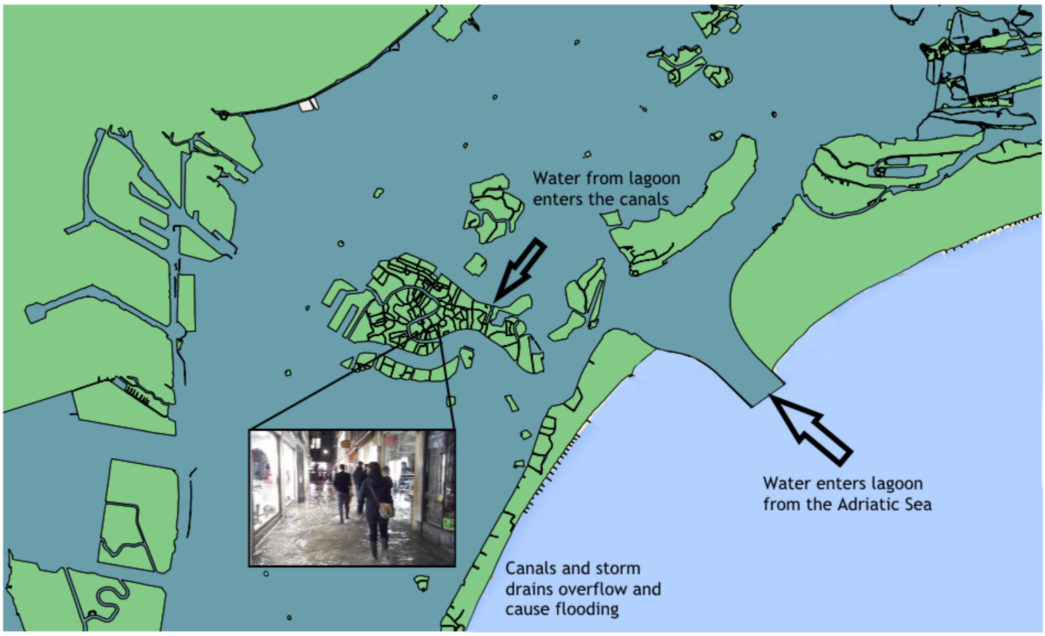


Figure A.1. Flood Graphic

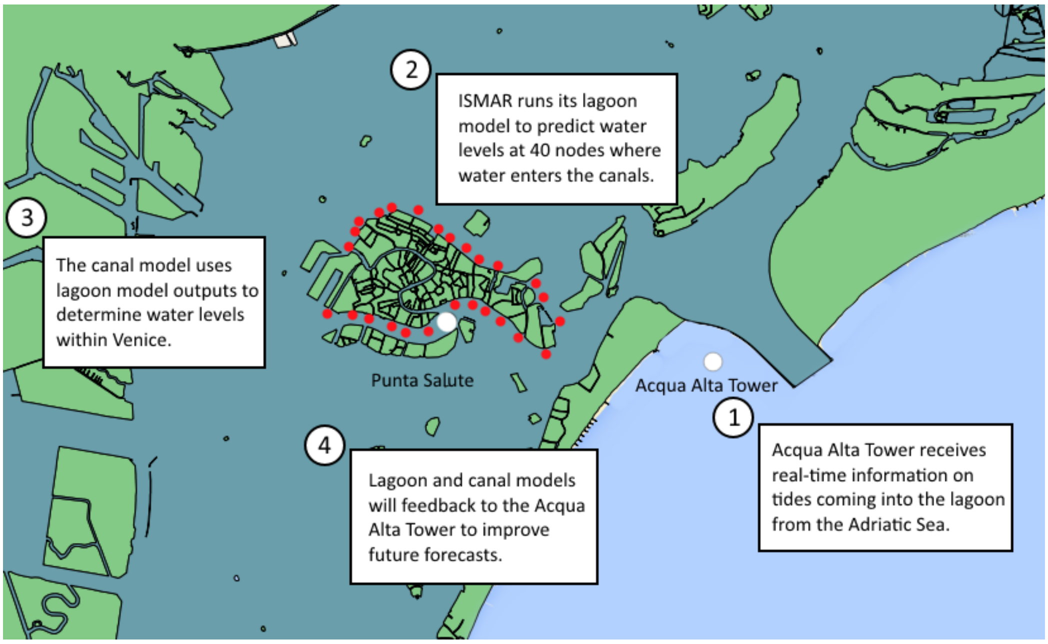


Figure A.2. Model Loop

Figure A.3. SHYFEM Lagoon Model

Appendix B - Cleverpole

The circuit for the sensor is composed of 192 resistors in series. Each resistor circuit is positioned a centimeter apart and is used to measure the height of the water based on a mathematical formula provided by Eraclit Venier SpA. As the tide level goes up, the resistors get covered by water and send a signal to the datalogger. Every five minutes, the sensor takes a reading of water level and sends an email to a secure account created exclusively for this project.

Whenever we wish to read the data sent by the sensor, we run a computer program provided by Eraclit. An algorithm decodes these emails and displays the water level information from the sensor.

Installation

Even though the sensor as a device has proven to be very precise, the measurements taken by the sensor can only be accurate if the installation was done correctly. In other words, incorrect readings, caused by a slanted sensor pole, for instance, are due to human error or imprecision. Thus, it's very important to invest time on the planning for the installation of the sensor. Otherwise, all the data gathered for a period of a day or two is worthless.

Constraints

There are many different aspects that have to be taken into consideration for the installation of the sensor. First, the region, the neighborhood or the group of islands is determined by the possibility of ISMAR's model outputting inconsistent water levels. For example, the first region that we chose for the installation of the sensor was around the Arsenale. The surroundings of the Arsenale face the interior parts of Venice. The behavior of canals is harder to model in these regions due to the concatenation of canal segments. The sensor would therefore serve as a calibration tool for the model in this location.

Another concern is the population density of potential locations. The sensor is a device that has an unusual appearance, thus its presence intrigues many of the pedestrians in the region. Some touch it, tilt it, or even switch it off. By accounting for the pedestrian density when we chose a location, the safety of the sensor can be ensured.

The sensor must also be well secured. Rising waters and boat wakes may cause movement of the sensor. It is critical to find locations that have handrails, a concrete pillar, and/or hooks to tie to the sensor and prevent it from slipping. As it can be seen in the **Figure B.1(a)**, the sensor is tied to hooks and to the pillar behind it to keep it straight.

Offset Measurement

As it can be seen in the next figure, the sensor is installed above a surface that, like all of Venice, is above the conventional zero water-level. The measurement of the ‘zero-mark’ is done by measuring the height of the surface immediately under the sensor.

This height is measured by taking the difference between the level of the upper pavement level and the lower pavement level, as seen in **Figure B.1(a)**. Next, another measurement is taken between the lower pavement level and the ‘zero-mark’, identified in between the two black adhesive bands in the sensor, as seen in **Figure B.1(b)**. Finally, we used the GIS pavement level in order to determine the upper pavement’s height and subsequently the height of the sensor’s zero-mark.

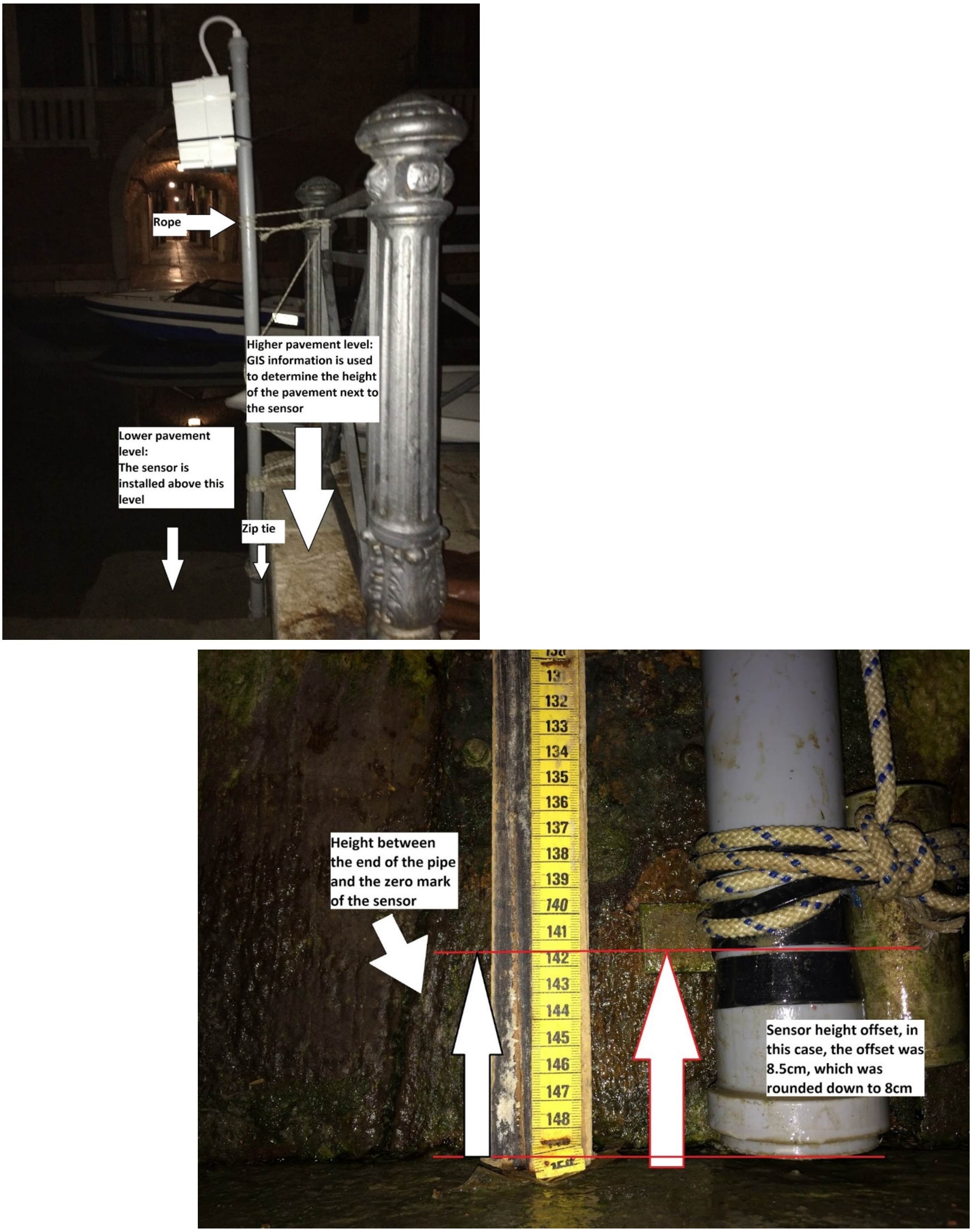


Figure B.1. (a, top) Installation process (b, bottom) Calculation of sensor offset

Appendix C – Tide Latency Maps

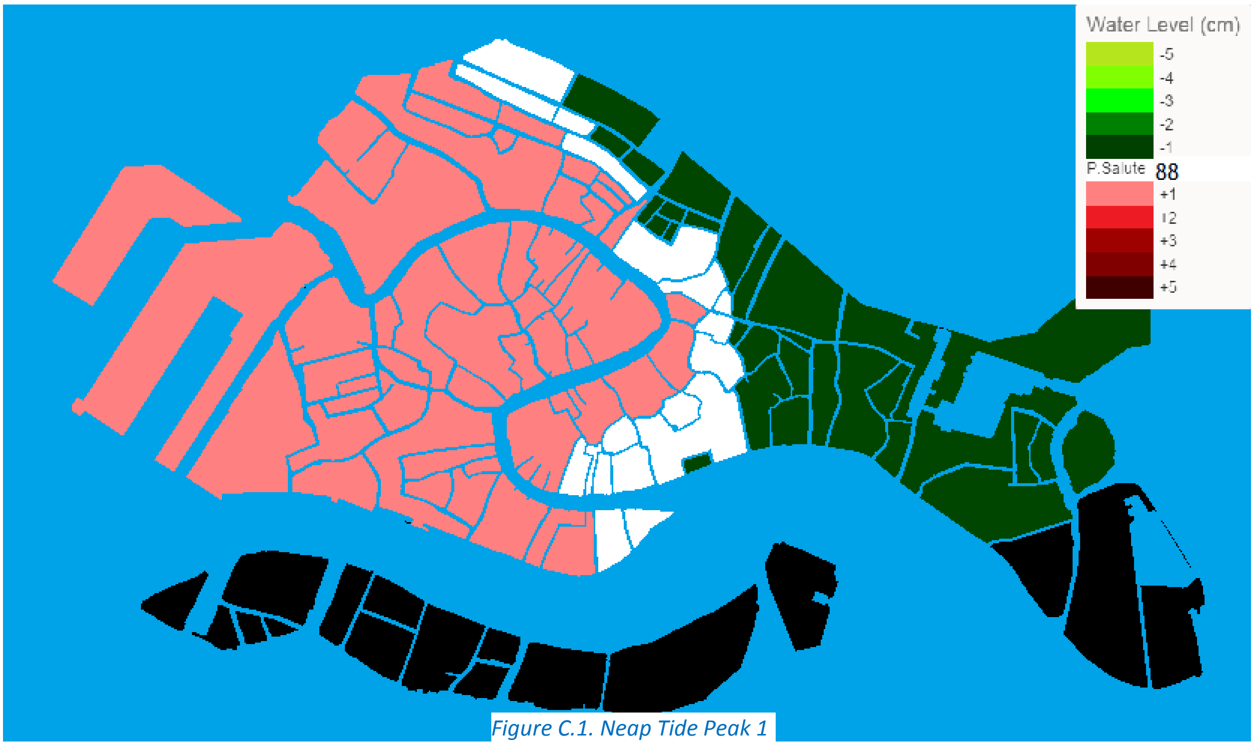


Figure C.1. Neap Tide Peak 1

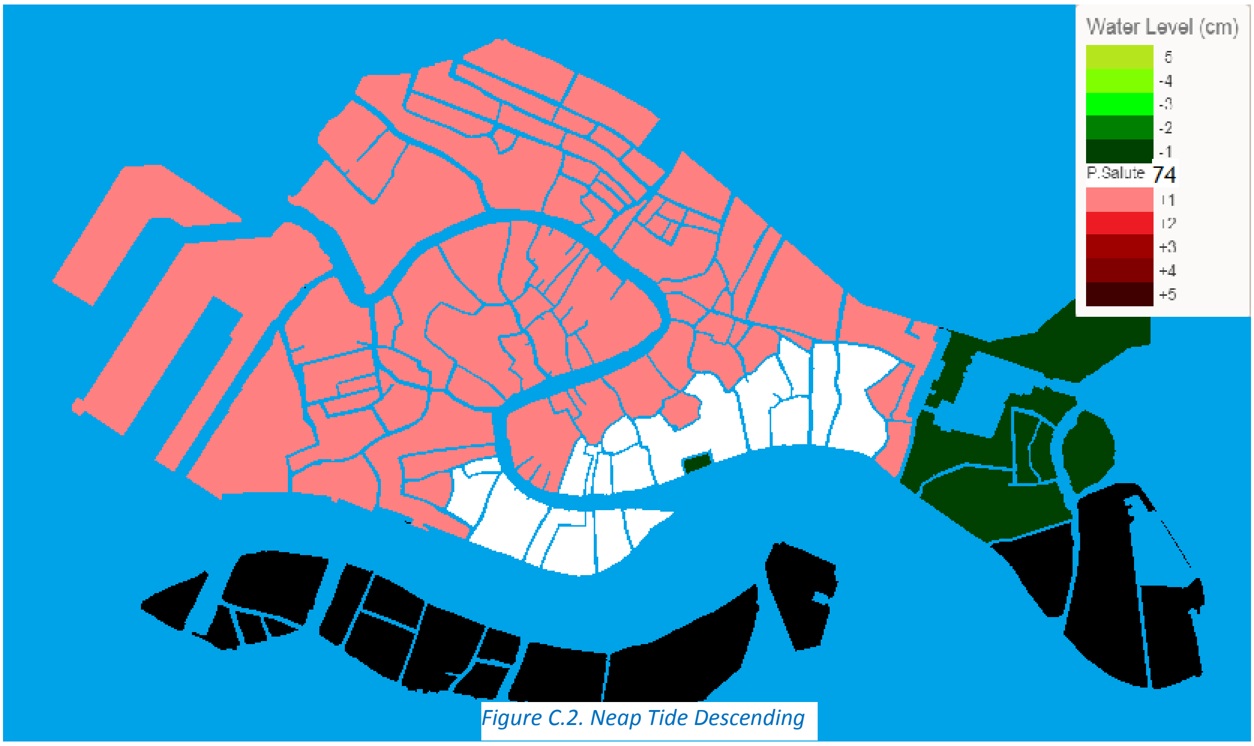


Figure C.2. Neap Tide Descending

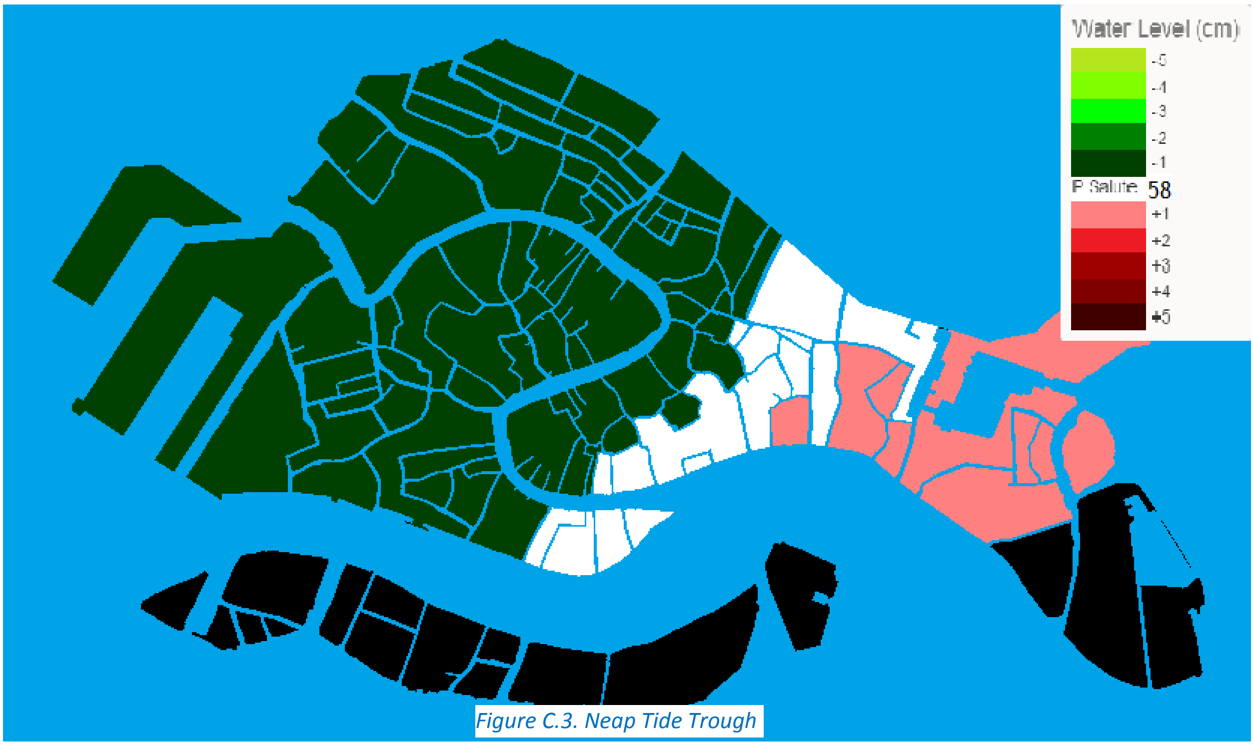


Figure C.3. Neap Tide Trough

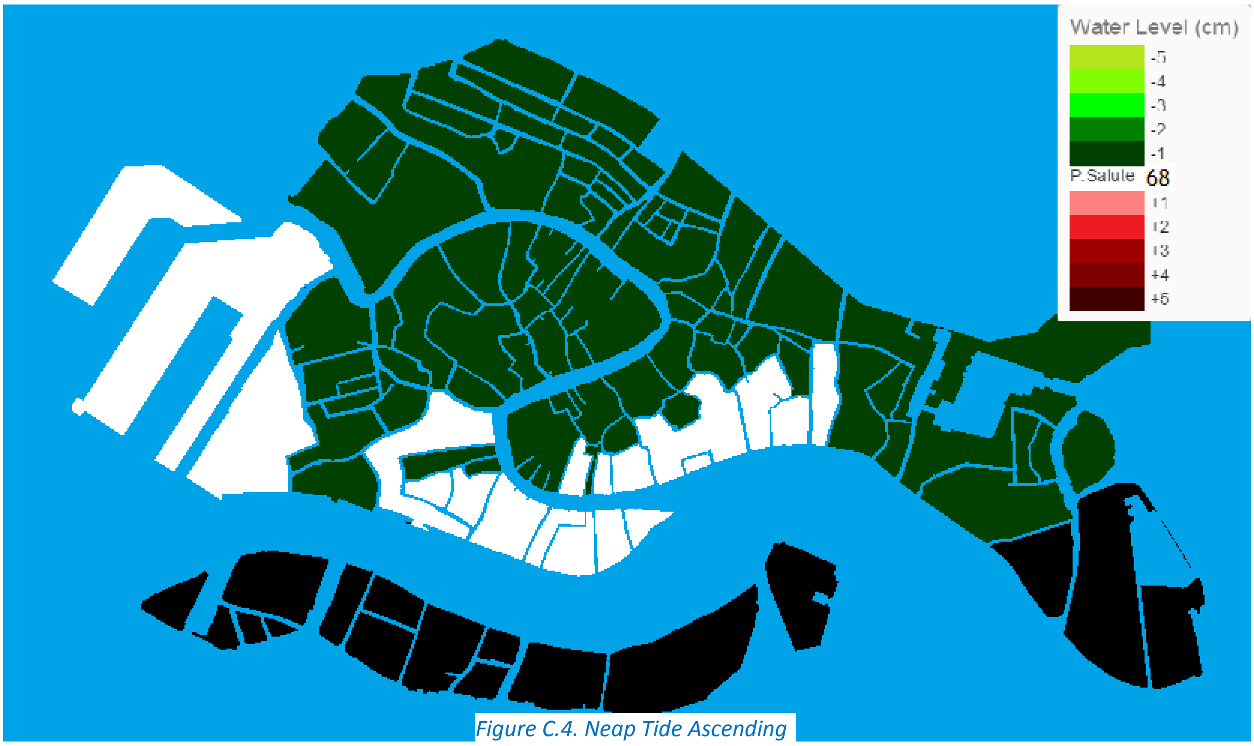


Figure C.4. Neap Tide Ascending

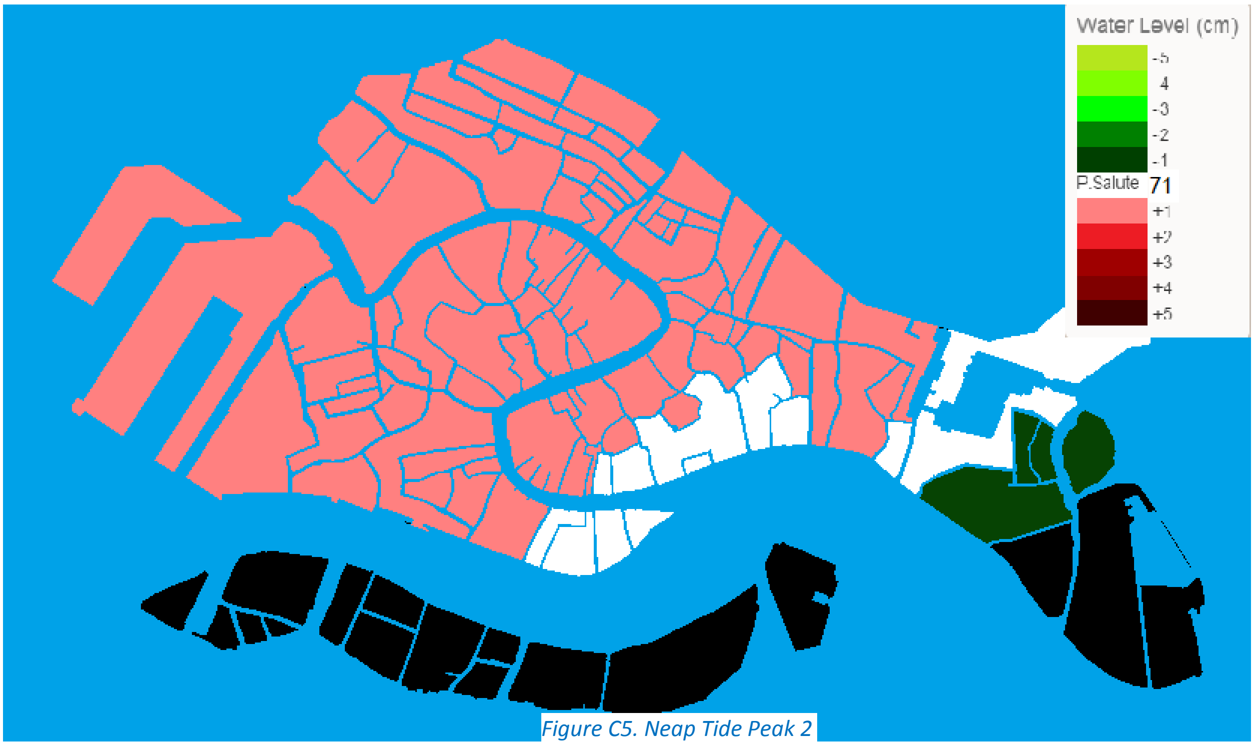


Figure C5. Neap Tide Peak 2

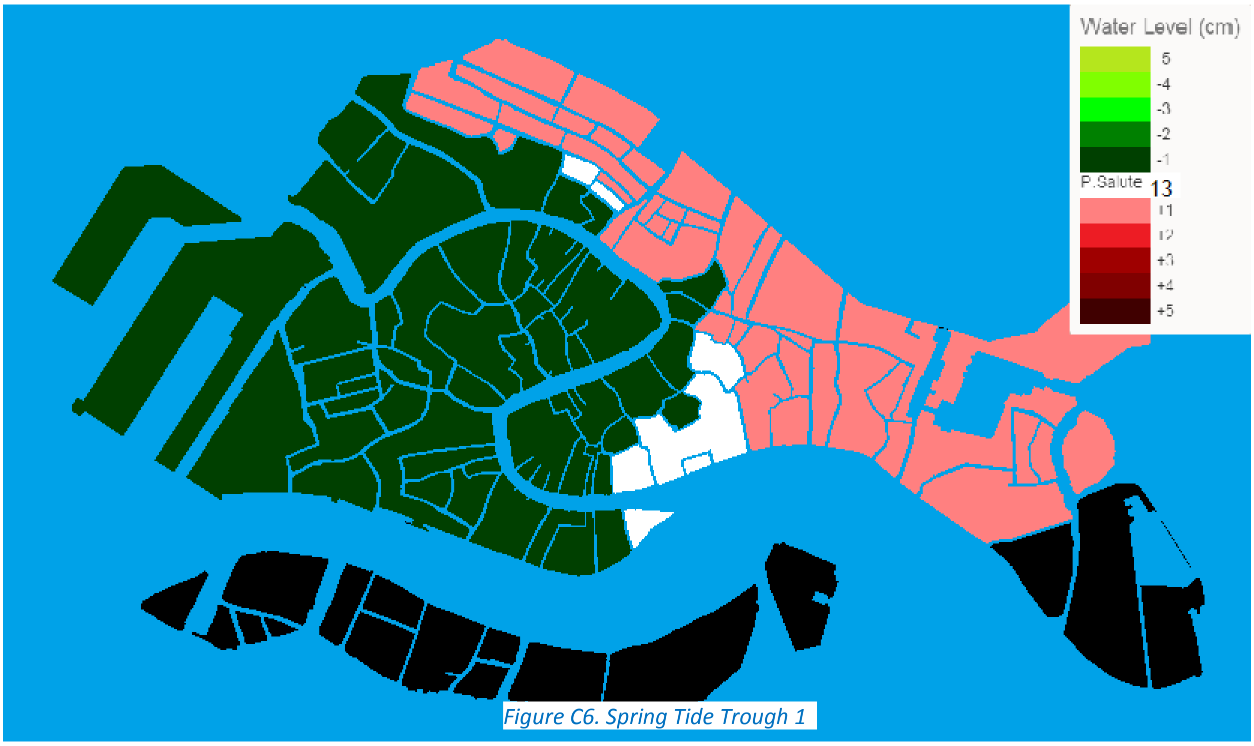


Figure C6. Spring Tide Trough 1

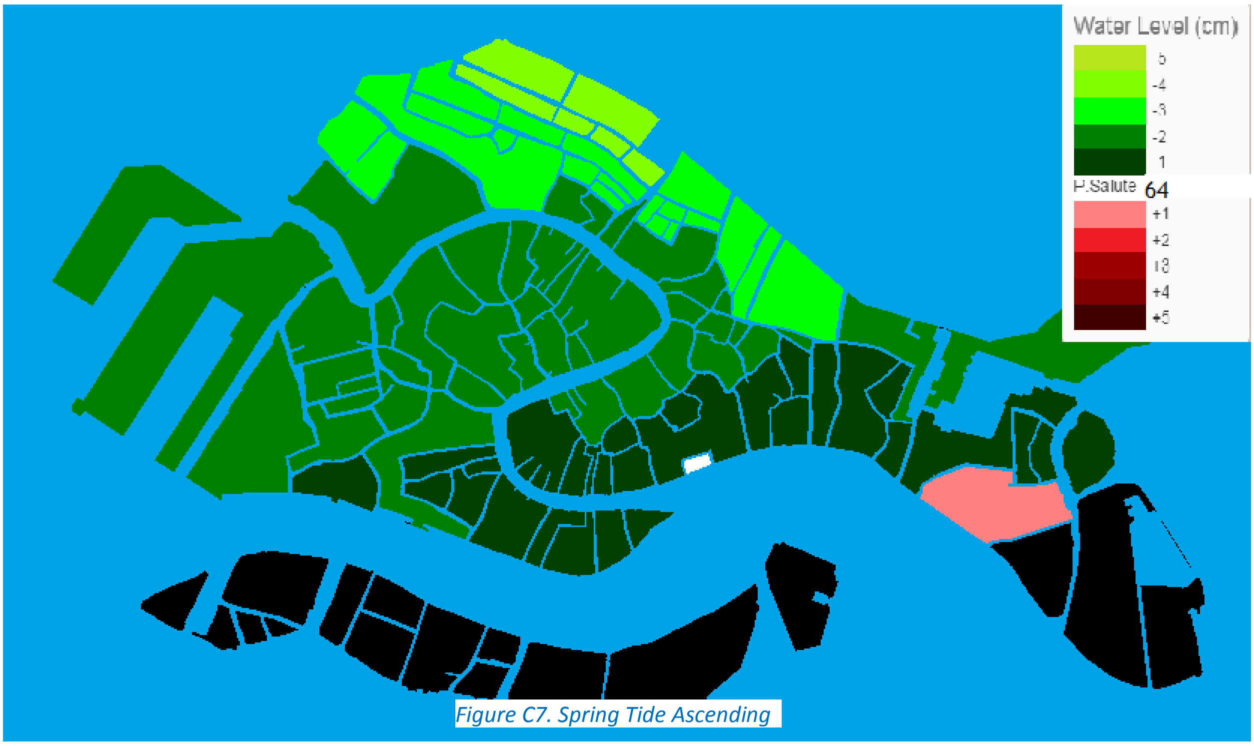


Figure C7. Spring Tide Ascending

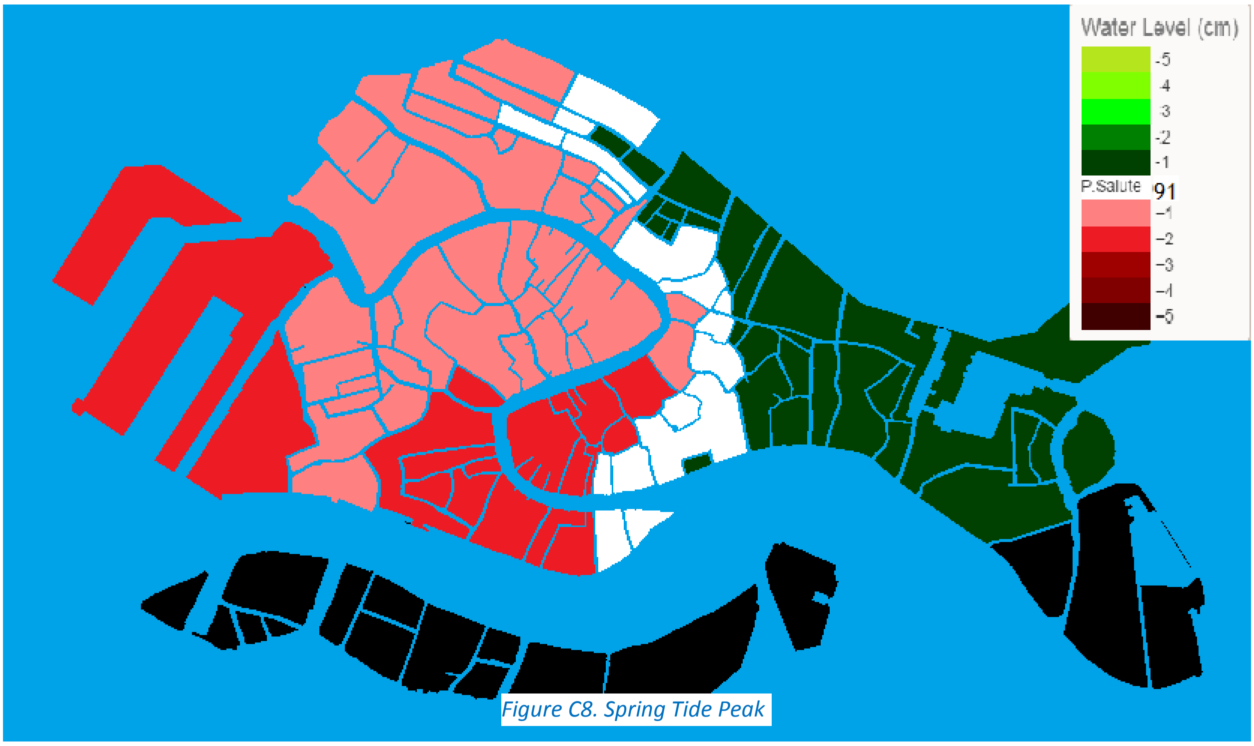


Figure C8. Spring Tide Peak

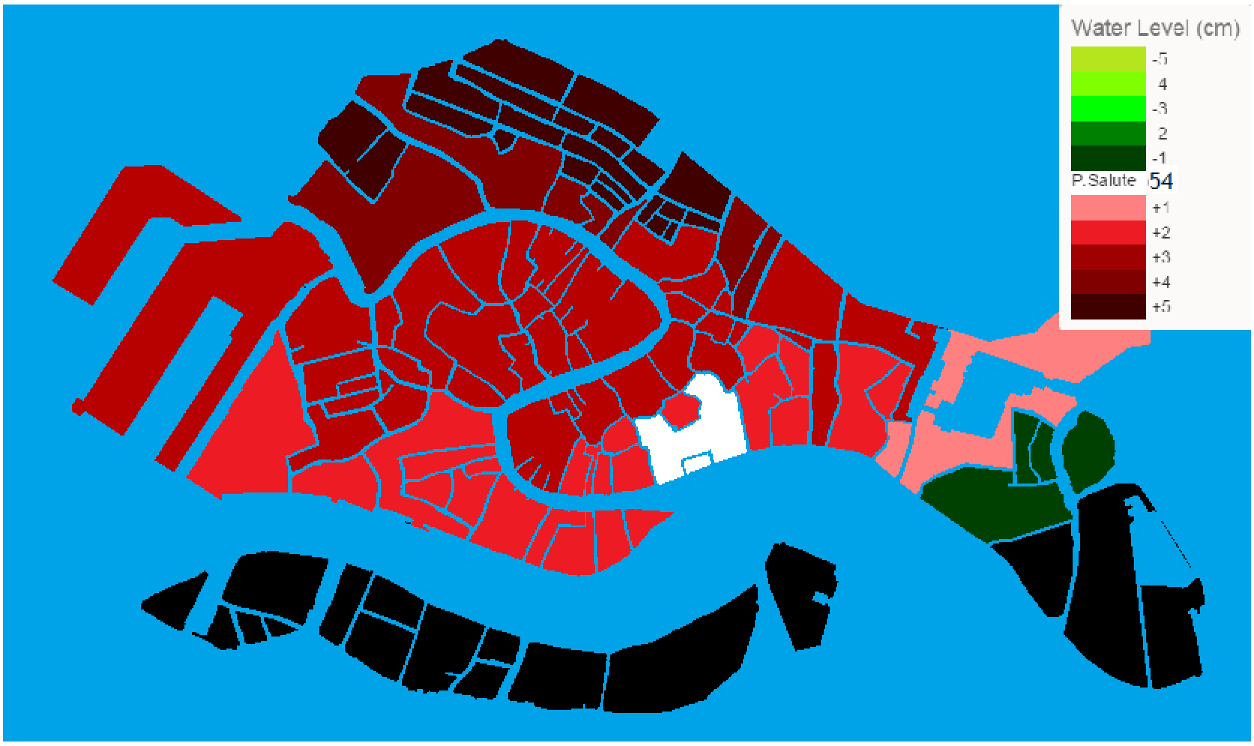


Figure C9. Spring Tide Descending

Figure C10. Spring Tide Trough 2