Project Number: FC VEI1

Hydrodynamics of the Inner Canals of Venice

An Interactive Qualifying Project

Submitted to the Faculty

of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
by

Christine L. Biscotti

Andrea M. Emery

Maxwell Pistilli

Joseph A. Zsofka

Date: July 30, 1999 Approved:

Prof. Fabio Carrera

Prof. Stephen Weininger

http://www.wpi.edu/~joe/venice.htm

Abstract

The canals of Venice are in need of constant maintenance because of sediment accumulation on canal floors. This accumulation of sediment results in problems for the city. Canals become too shallow to allow boat passage, sewer pipes clog which cause them to burst and accelerate wall damage to buildings, and health risks increase because of the presence of raw sewage.

A complete characterization of the water flow through the canals is necessary for the creation of an effective schedule that will prevent severe damage caused by sediment. For this reason, a sedimentation model is being developed by the Institute for the Study of the Dynamics of Great Masses that is co-sponsored by Insula S.p.A. and UNESCO-ROSTE, the sponsors of this project. Our goal was to measure the maximum flow velocity that will be used to verify the sedimentation model, and be combined with other canal data for the purpose of developing an improved canal maintenance schedule.

Maximum velocity data were obtained and used to calculate the Flushing Index, a number that measures the relative flushing ability of water flow through a canal. This number was then compared to sediment accumulation data. We observed that those canal segments with higher Flushing Indices had lower levels of sediment accumulation than those canals with lower Flushing Indices. This information will be useful in determining which canal segments will require more frequent sediment removal, allowing an effective long-term maintenance schedule to be developed that will minimize the problems caused by sediment accumulation.

Acknowledgments

We would like to acknowledge Professor Fabio Carrera, Director of the Venice Project Center (VPC) who made our project possible and a success. He provided insight and ideas for our project. We would also like to recognize our other project advisor, Professor Stephen Weininger, for editing our paper, giving presentation suggestions and answering our additional questions. We also appreciate Alberto Gallo from the VPC for his assistance in computer related questions and Italian translations.

Our sponsors, UNESCO and Insula S.p.A. deserve great recognition for their interest in and contribution to our project. We also thank the *Centro Maree* for providing daily tidal forecasts to give us a more accurate estimation of measurement times for our data collection.

Authorship Page

This project was fully a group effort. The four members contributed equally to the research, gathering of data, analysis, and final write-up.

Table of Contents

List of Figures

List of Appendices

Chapter 1 – Introduction

The canal system of Venice has served as the main means of transportation and sewage removal since the founding of the city and still does so today. However, many current-day problems exist with the canal system because of environmental threats and a lack of maintenance. Our project focuses on the issue of tidal velocity in the Venetian canals because it is the tidal flow that removes suspended sediment from the canals. When the tidal flow is not strong enough to remove the solids contained in sewage effluents, sediment accumulates on the canal floor and must be removed by dredging which is expensive and disruptive. Our maximum velocity measurements taken for every target canal segment will be used to validate a sedimentation model developed by the Institute for the Study of the Dynamics of Great Masses, a division of the National Research Council of Italy (ISDGM-CNR). This model characterizes the flow of water through the canals and will help in the creation of a canal maintenance schedule, which will enable the city to prevent damage to canal walls and keep canals open to all boat traffic.

The primary sponsor of our project is the United Nations Educational, Scientific and Cultural Organization, Regional Office of Science and Technology in Europe (UNESCO-ROSTE). Insula S.p.A., a Venetian company responsible for the maintenance and repair of the canal system, will be the final beneficiary of the model that other UNESCO researchers will develop and test with the data collected by this team.

This project report, *Hydrodynamics of the Inner Canals of Venice,* contains all the information necessary for a good scientific understanding of how tides function within the canal system. The **Executive Summary** is a synopsis of the entire project, giving details of its purpose and how the goals of the project were achieved. The **Background** introduces the physical processes that affect the tidal flows. It gives a history of the Venetian canals and their current state of maintenance, and describes those general properties of water that affect its flow through the canals. Previous studies are introduced to describe past research methods as well as to identify problematic areas and inaccuracy in existing data. The **Literature Review** presents summaries of each of the sources used in the Background. The **Methodology** section gives detailed information about how we conducted velocity measurements and the tools used. **Results** presents the field data and describes the four main hydrodynamic categories of canals in Venice. The **Analysis** section examines patterns found in the velocity data collected and its correlation with pre-existing sediment data. The **Conclusion** uses these patterns to determine which canals will need more frequent maintenance. **Recommendations** is the section in which we describe areas of possible further study.

Chapter 2 – Executive Summary

This report, prepared for the United Nations Educational Scientific and Cultural Organization (UNESCO), characterizes the hydrodynamic behavior of the inner canals of Venice with regard to maximum flow velocity.

For the past 30 years, the maintenance of the canals has been irregular, resulting in the accumulation of sediment. For this reason, the inner canals of Venice are in need of regular maintenance. A scheduled maintenance program increases the functionality of the canal system by easing the passage of boats and preventing the clogging of the sewer holes, which directly dispose effluents into the canals. With the cooperation of UNESCO, Insula S.p.A. is organizing a planned maintenance schedule to effectively dredge and clean the inner canals in a logical manner. To do this, they are using a sedimentation model created by the Institute for the Study of Dynamics of Great Masses, a division of the National Research Council (ISDGM-CNR). The purpose of this project is to obtain maximum flow velocities of the canals to validate this flow model, and thus help in the creation of the maintenance schedule.

The network of the Venetian canal system is very complex. The flows of all the canals are interdependent because they are all connected. These intersections result in the flows of the individual canals being affected by other canals. Therefore, in our study the canals are divided into segments defined by the points of contact with other canals. In this report, the individual segments are the basic units of study.

The canal flows are influenced by the flow of the Lagoon channels, which are determined by the Adriatic tides. The most significant effect on tides is the lunar cycle. The *Centro Previsioni e Segnalazioni Maree* of the *Comune di Venezia* uses the lunar cycle and other astronomical and morphological factors to produce tide charts, which forecast the amplitudes and timing of the incoming and outgoing daily tides. Tides have the most variance in amplitude during the new and full moon cycle, thus causing the speed of the water as it flows through the canals of Venice to be at its maximum during those periods.

In order to obtain maximum velocity flow measurements, we used a systematic data collection technique. With the use of a flotation device and detailed schedules based on the tide charts, maximum velocities were obtained for 133 out of 199 canal segments that we targeted for data collection. We did not measure the remaining 66 segments because they were either being dredged, were immeasurable using our method, or were unreachable by foot. Twenty-three of the segments that we did measure most likely displayed altered flows due to nearby canals being blocked off for dredging. The data for these segments will be used for further study of the effects that a blocked canal has on the flow of the entire canal system.

By combining our velocity data with sediment accumulation data collected by past studies, we were able to determine that maximum flow velocity was not the only factor determining sediment removal. By combining the length of the canal segment along with the velocity of the water we were able to give each segment for which there was sediment data a flushing index number. We found a direct correlation between this Flushing Index number and the amount of sediment build up in the segment. This enabled us to determine that in the canals with a higher index number, sediment was being more effectively removed. This project also provided data regarding the direction of water flow during ascending and descending tides. This was especially important for the validation of the flow model since many canal segments do not follow the flow patterns one would intuitively expect. Future studies that finish data collection and take measurements to determine how blocked canals affect the flow in surrounding areas would greatly improve the accuracy of the flow model.

This project successfully accomplished the goal of completing the hydrodynamic characterization of the accessible inner canals of Venice. The data found in this report can be used to validate the sedimentation model and aid in the creation of a maintenance schedule. The creation of a long-term maintenance schedule will allow residents and businesses to prepare in advance for the inconveniences associated with the closing of canals. This advanced planning will also give the city the opportunity to clean the canals before conditions cause extensive damage to canal walls and surrounding buildings.

Chapter 3 – Background

Our background chapter covers several areas about which information was needed prior to carrying out this project. This chapter will familiarize the reader with essential topics appearing in subsequent chapters of this report. Our discussion includes information about our sponsors, the physics of tides, maintenance of the canals, and the importance of timing to our velocity measurements.

3.1 Sponsors

Our two sponsors, UNESCO-ROSTE and Insula S.p.A., both deal with many issues related to the welfare of Venice, including scientific research, artistic and architectural conservation, as well as canal dredging, restoration of canal banks, protection from flooding, and the re-organization of the underground utility grid.

3.1.1 UNESCO

UNESCO is an agency of the United Nations that was created in 1945 to help maintain peace throughout the world by promoting collaboration among all nations in the areas of education, science, culture, and communication. It focuses on promoting universal respect for law, human rights, and fundamental freedoms without regard to race, religion or sex. UNESCO is composed of representatives from 186 countries world wide, and is headquartered in Paris, France.

UNESCO promotes partnership through five primary functions, the first being the sponsorship of prospective studies used to further the development of the goals that UNESCO strives to accomplish. The second function is the transfer, advancement, and sharing of knowledge. The third is the setting of international standards for actions such as the preservation of the Venetian ecosystem. The fourth is to provide technical expertise to member countries in forms such as joint venture projects. The last function provides for the exchange of specialized information among member countries.

UVO, the UNESCO Venice Office, formed in 1988, is involved in technology and science in the Mediterranean region and Eastern Europe. ROSTE's main goals are to promote research, develop training activities, and provide an opportunity for communication among research scientists through sponsorship of their attendance to special workshops. It concentrates on the sharing of knowledge in the natural and environmental sciences and attempts to preserve heritage and culture. ROSTE's main focus is on environmental problems, especially those dealing with the ecology of Venice. It collaborates with many colleges and universities and is funded by several organizations, including the Italian Ministry of Universities and the Italian National Research Council.

3.1.2 Insula S.p.A.

Insula, "*Società per la Manutenzione Urbana a Venezia*," is a corporation that focuses on the maintenance of Venice. It is owned by the city of Venice (52%), ASPIV (the Venetian waterworks), Ismes (part of the electric utility company), Italgas (the natural gas company), and Telecom Italia (the telephone company), each of which owns 12% for a total of 48%. Insula S.p.A. was incorporated on July 10, 1997, and established three main objectives: speeding up the dredging of canals, restoring the canal banks and the ancient sewer system, and implementing local protection measures against high tides, known as *'acqua alta'*.

3.2 The Canal System

The canals in Venice are an integral part of daily life. They serve as the primary mode of transportation as well as the sewage removal system for the city. Since this report contains discussion of the city in terms of areas known as *sestieri*, as well as individual canals, it is helpful to be familiar with the location of each *sestieri* as well as the major canals (Figure 1).

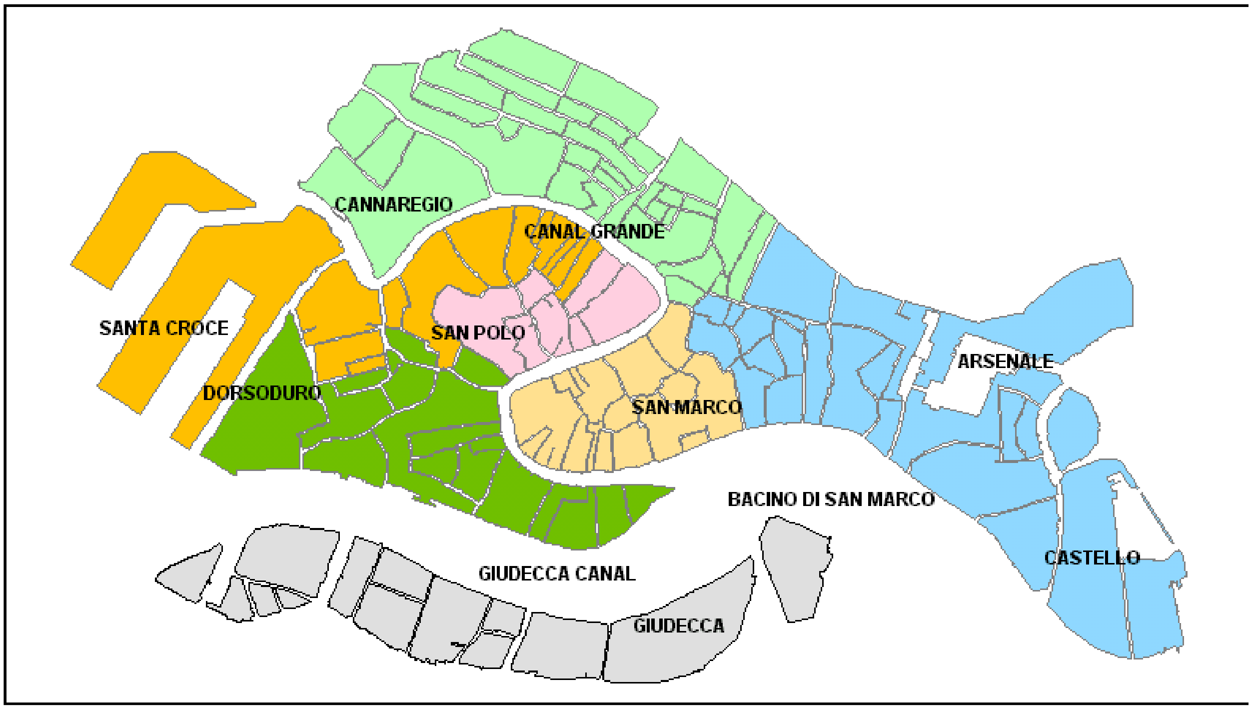


Figure 1: Names and locations of *sestieri* and major canals

3.2.1 Canals as Transportation Arteries

The canal system of Venice is the main transportation network. With daily boat traffic, it is imperative that the canals are kept navigable and that water levels are kept at a safe depth for boats to pass. However, sediment accumulates from the sewage directly entering the canals and plaster falling from the walls of buildings, making some segments impassable, especially during low tides. This forces emergency boats to take longer routes in order to reach their destination, which increases response time and endangers lives.

3.2.2 Canals as the Venetian Sewer System

The cleanliness of the canals is a serious concern. Waste from buildings and houses is dumped into the canals because there is no modern sewage system. Since waste is deposited directly into the canals, it poses health risks to those who come in contact with the water. Waste dumped into canals also creates mud deposits, which reduce the navigable areas of the canals.

3.2.3 Canal Maintenance and Structural Damage to Buildings

Since the upkeep of canals has been minimal in the past 80 years, damage has occurred to many building foundations located along the water. A previous WPI study concluded that the primary cause of structural problems is the clogging of sewer pipes adjacent to canals.[1] When the pipes clog they often burst, causing the material to seep through building walls along the edges of the canals, weakening the building foundations. Tides, saltwater, and boat traffic also contribute to the deterioration of the sides of buildings, causing bricks and plaster to fall into the canals.

3.3 Maintenance of Canals

Canal maintenance has been a necessary part of Venetian life since Venice became the capital of the Venetian Republic around 810 AD. Systematic efforts at maintaining the canals were not made, however, until the city began planning maintenance in 1994.

---

[1] WPI IQP Analysis of Sewer Holes and Canal Wall Damage in Venice, Italy (E'98).

3.3.1 History of Canal Maintenance

Canal maintenance was irregular from the founding of the city until 1866, when Venice became part of the new Kingdom of Italy and canal maintenance became a concern of the new government. In fact, excavation of sediment did not even begin until 1869 after an extremely high tide caused severe damage to many of the canal walls and buildings of Venice, making the need for dredging apparent.

Since 1993, a new program for planning and scheduling regular canal maintenance has been implemented. Insula S.p.A. produced a cleaning schedule, which includes full excavation of every canal in Venice over the next 30 years. Since 1990, WPI studies have collected extensive data about many aspects of the canals, which have helped with the planning of canal maintenance.

3.3.2 Methods of Maintaining Canals

Canal upkeep is a very important part of ensuring that Venice remains a livable, beautiful city. An important aspect of canal maintenance is the dredging of canals to remove built up sediment. Excavation is required to remove this sediment, which consists mostly of organic material. The accumulation of sediment is the result of sewage being dumped directly into the canals. Much of this sewage is washed out with the tides, but enough remains in the bottom of the canals to cause health risks and navigational hazards if it is not effectively removed. Since boat travel is the main method of transportation in Venice, it is important that all canals be well maintained, not only for convenience but for the emergency vehicle routes as well. Until recently, the dredging was prompted by how difficult it was for emergency boats to navigate through the canals.

There are two ways of excavating the canals, dry dredging and wet dredging. The dry method requires the workers to completely drain the canal before removal of the sediment (Figure 2). Although dry dredging costs more money and time, it is the method commonly used for planned maintenance since it is effective at thoroughly removing the sediment and allows for canal wall repairs. Wet dredging is the process of removing sediment while water remains in the canal. It does not allow for any repair of canal walls, and although faster, it is much less effective than dry dredging. Due to its deficiencies, wet dredging is used only when emergency cleaning of a canal is needed. Both the city and the owners of the buildings along the canals being dredged pay for planned maintenance of canal walls during dry dredging. Emergency maintenance is generally paid for by the city. The actual maintenance work is bid out by Insula S.p.A. to private contractors.

Figure 2: An example of the dry method of canal dredging

3.4 Major Factors Affecting Water Flow in the Canals

There are three major factors that affect the water flow through the canals in Venice: the tides coming from the Adriatic Sea, the interconnections within the canal system, and long term climatic changes.

3.4.1 Adriatic Tides

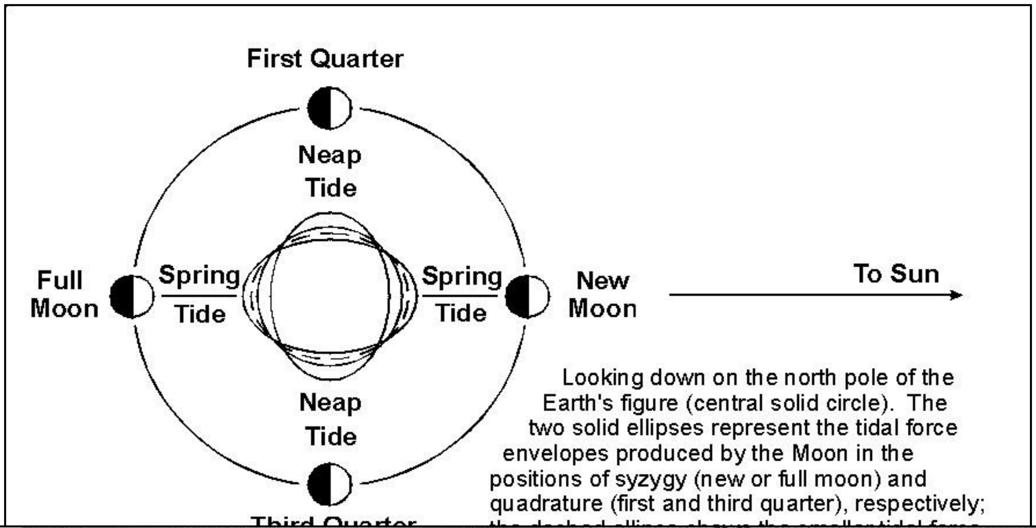
Although Venice does not directly border an ocean or sea, it is completely surrounded by the Venetian Lagoon, which is connected to the Adriatic Sea. The tides from the Adriatic control the water level of the Lagoon, which in turn affects the water level of the canals in Venice. As a result, the water in the canals experiences the fluctuation of the tides in the Adriatic. These tides are influenced by three factors: astronomical, morphological, and meteorological effects.

3.4.1.1 Astronomical Effects on the Tide

Since the canals are affected by the tides of the Lagoon, it is necessary to understand how the tides behave. The Sun and the Moon are the primary causes of the tides. Both affect the tide's magnitude and periodicity. By understanding how the Sun and Moon influence the tides, scientists at the *Centro di Maree* (section 3.5.1) are able to predict what the tide cycle will be for Venice during a specific time period. Appendix A contains detailed information about the solar and lunar effects on the tides.

3.4.1.1.1 Effects of the Moon on the Tides

The Moon's gravitational force causes the water on the Earth's surface to be pulled toward it, thus generating tides. Relative to a fixed point on the Earth, the lunar cycle is 29 days long and consists of four phases; the full and new moons, known as *sizigie* in Italian*,* and the half waning and half waxing moons, known as *quadrature* in Italian. *Sizigia* occurs when the Moon is directly above or directly opposite the area experiencing it. This position in the lunar phase causes the Moon's gravitational effect on the Earth to create tides which are more extreme than during the *quadratura,* when the position of the Moon is between the new and full moons relative to the fixed point (Figure 3).



Looking down on the north pole of the Earth's figure (central solid circle). The two solid ellipses represent the tidal force envelopes produced by the Moon in the positions of syzygy (new or full moon) and quadrature (first and third quarter), respectively;

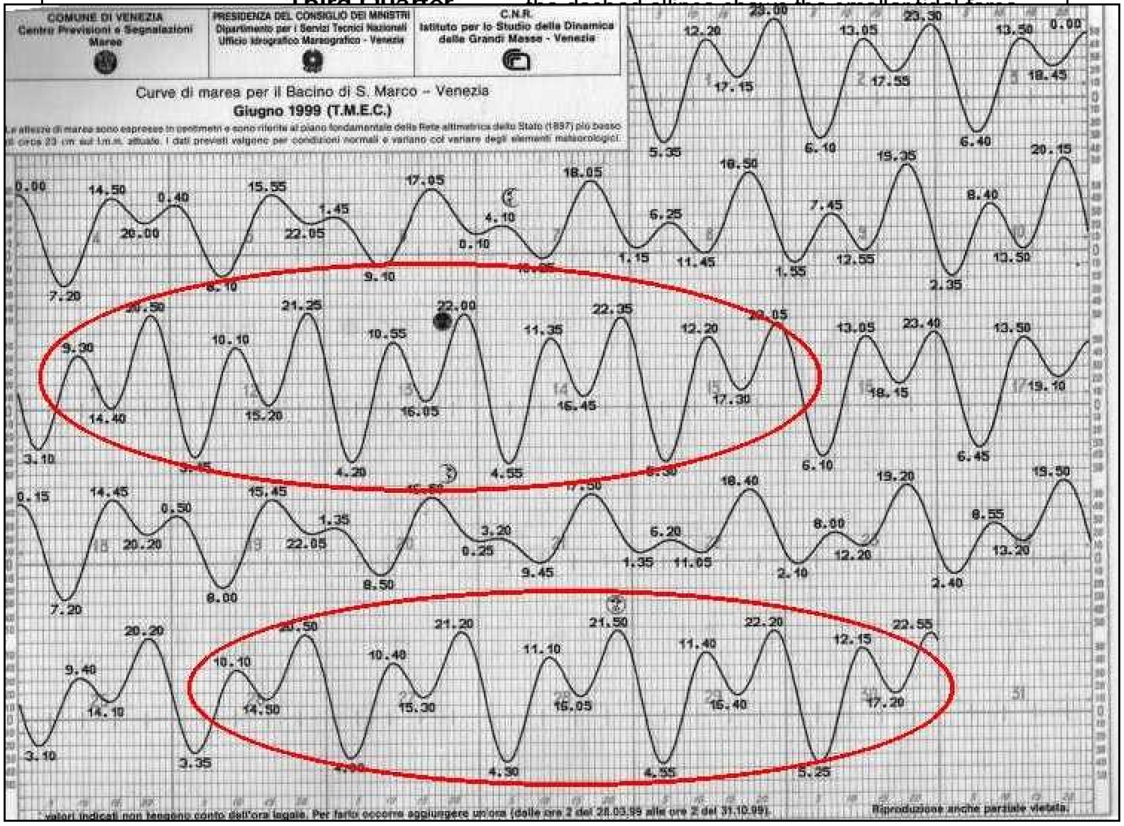


Figure 4: A tidal forecast for *il Bacino di San Marco-Venezia*, June 1999

Figure 4 is the tide forecasting chart for the month of June, 1999. Each box represents a day, with the date marked in the lower center of each box. The curved lines in this tide chart show the amplitude of the tide, with the incoming tide having a positive slope and the outgoing tide having a negative slope. High tides are represented by the peaks of the curves and low tides by the troughs. The numbers in black indicate the times the high and low tides are expected to occur using solar time. The *sizigie* for this month occurred during the weeks of the 13th and 28th, circled in red. A greater fluctuation in tidal height during the weeks of the *sizigie* than during the weeks of the *quadrature* is apparent. The maximum velocity of the water flow is found at the midpoint between high and low tides. The use of tide charts (Appendix B) helped us make a schedule for taking velocity measurements (Appendix C).

3.4.1.1.2 Effects of the Sun on the Tides

The Sun also affects the magnitude of the tides. The distance between the Sun and the Earth is much greater than the distance between the Moon and the Earth, causing the Sun to have less of a gravitational effect on the Earth. This causes the Sun to affect the tides in a similar manner as the Moon but with less force. At noon or at midnight, when the Sun is directly above or on the direct opposite side of the Earth from a fixed point, it has an enhancing effect on the tides that are created by the Moon. Halfway between these times, at 6:00 and 18:00, the sun has a diminishing effect on the tides. These enhancing and diminishing effects create the most extreme tides around midnight and noon of the *sizigie*, and the least extreme tides during the morning and evening of the *quadrature.*

3.4.1.2 Meteorological Effects on the Tides

Major winds also affect the cycles of the tides. For example, in the northern part of the Mediterranean Sea, a cold wind called the Bora flows in a north to south direction, at speeds of up to 100 knots.[2] It is mainly present during the winter and during stormy weather, and is bounded by the Swiss Alps, the Appenines of Italy and the Balkans. The other strong wind is the Sirocco, which is a hot wind that forms over Libya and Egypt. It blows in a northerly direction across the Mediterranean Sea, causing rain, fog and the build up of moisture (Figure 5). These winds have an effect on the tides of Venice. If they are blowing against the direction of the tides, the water will enter the city more slowly, and if they are blowing in the same direction as the tides, the water will move into the city more quickly than if the winds were not blowing at all.

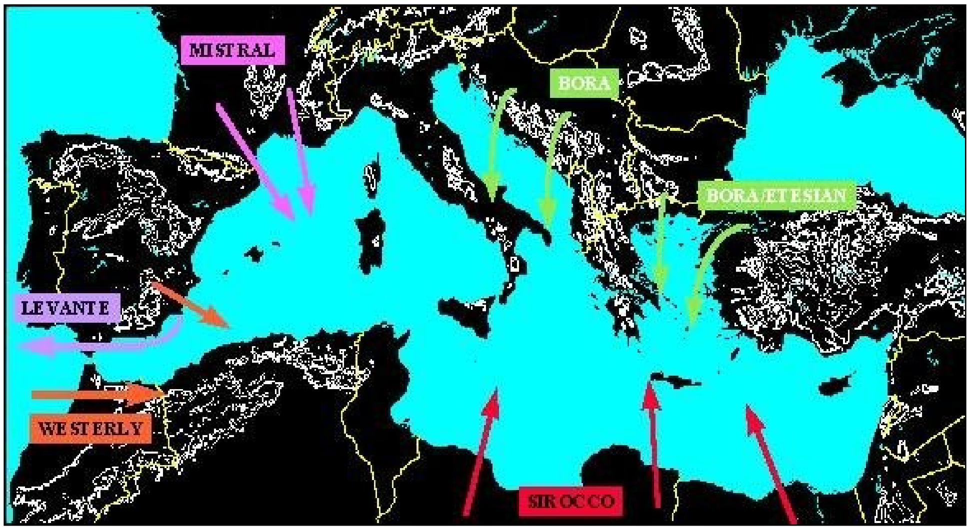


Figure 5: Winds affecting the Adriatic Sea

A smaller influence on the height of the tides is the change in barometric pressure. High pressures contribute to a decrease in the height of tides and low pressures cause an increase in the height.

---

[2] Naval Research Laboratory, http://www.nrlmry.navy.mil/~medex/tutorial/medex/winds/wind_all.html.

3.4.1.3 Morphological Effects on the Flow of Water Through Venice

Another impediment that restricts the flow of tides through the canals is friction with the canal walls and floor. This friction causes the water near the canal walls and floor to be slower than at the center of the canal.

3.4.2 Interconnections of the Venetian Canals

Venice is composed of 182 inner canals called *rii*. These canals connect with each other, forming a network throughout the city. Each time a canal is intersected by another canal, the flow of the water is altered. This makes it impossible to gain accurate hydrodynamic data without studying individual sections of the canals.

The canals are divided into smaller segments in order to account for the discontinuity caused by the difference in the movement of water created by canal intersections. A new segment begins every time a canal is intersected by another canal (Figure 6) or by a *rio terà*, as explained in section 3.4.2.1. In order to circumvent ambiguities in the naming of the canals, we used the naming system developed by past WPI project groups and adopted by UNESCO, the City of Venice, and Insula S.p.A., making it the official standard for all canal references in Venice.

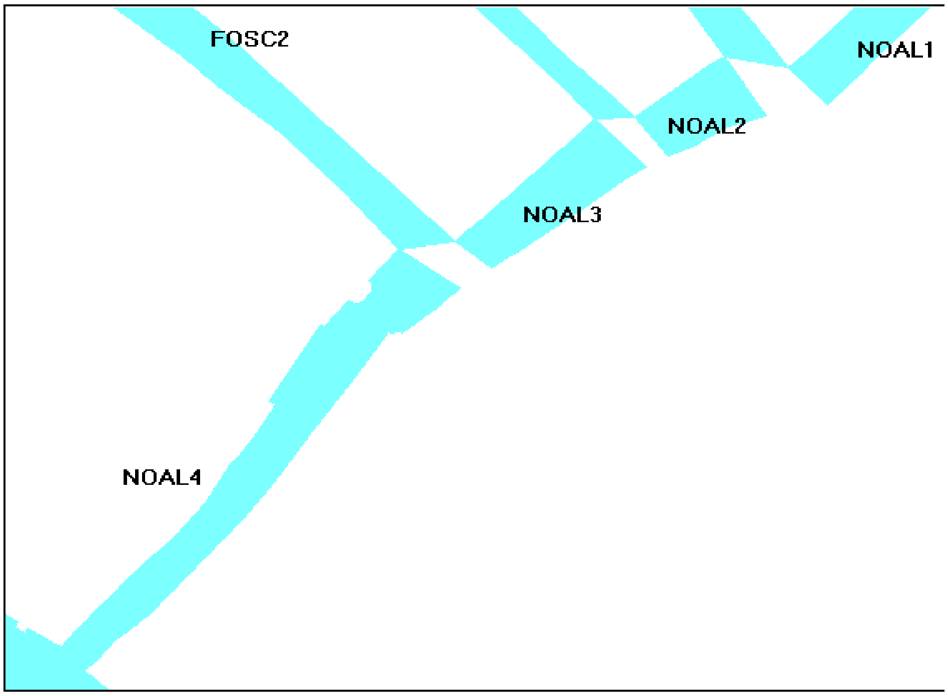


Figure 6: Example of Rio de Noal divided into segments

3.4.2.1 Rii Terà

The term '*rii terà*' refers to canals that have either been completely filled in or canals that have been covered over: *rii terà tombati* and *rii terà con volti*, respectively. Whether the canal is filled in or covered affects the flow of water in adjacent canals differently (Figure 7).

Rii Terà Tombati are represented by orange in Figure 7. Since no water is flowing through these canals they do not affect the flow of water in adjacent canals. When a canal is intersected by a *rio terà tombato*, the two segments are treated as though they were one segment.

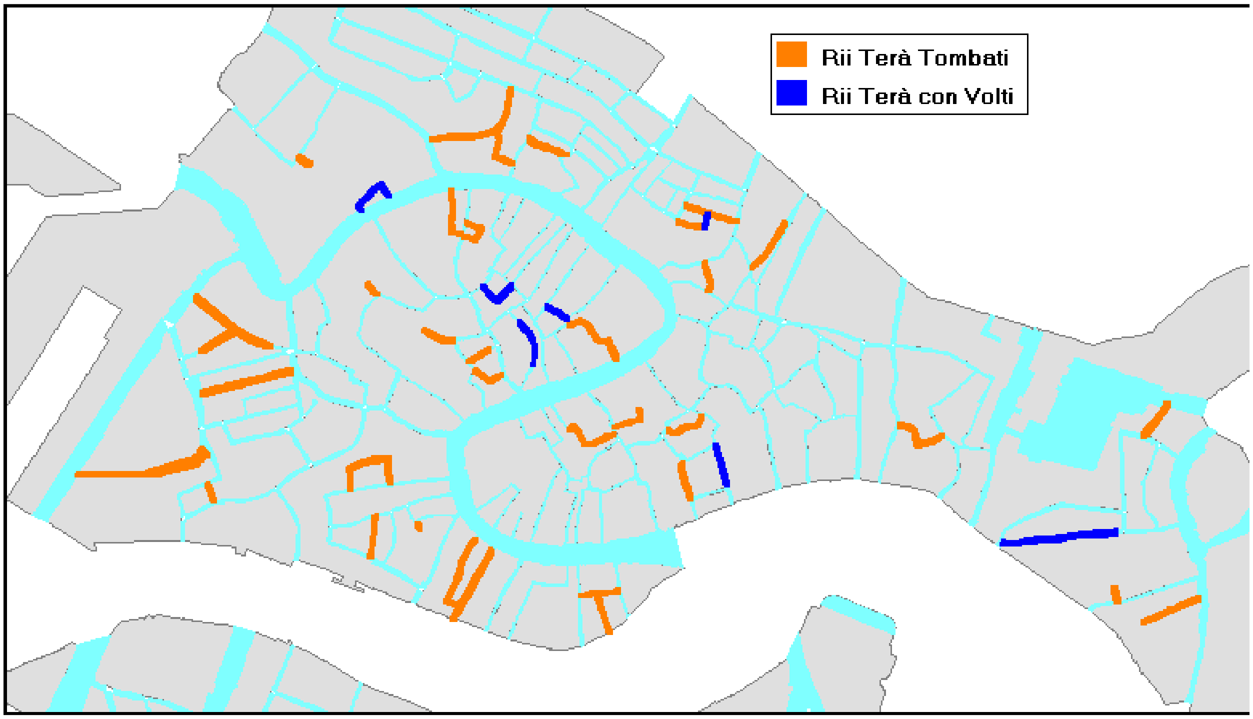


Figure 7: Map of *Rii Tera* in Venice

Rii terà con volti are represented by blue in Figure 7. Because water still flows through them, they act like regular canals. Therefore, when a canal is intersected by a *rio terà con volto*, the two segments thus created are treated as though they were a regular canal intersecting the canal being studied.

3.4.3 Long Term Changes That Will Affect Canal Water Levels

There are several global environmental changes as well as changes in the areas near Venice that will, over time, affect the tides and thus the water level of the city. These changes include subsidence, eustatism, and global warming.

3.4.3.1 Subsidence and Eustatism in Venice

Subsidence[3] of the earth under Venice and eustatism[4] in the Lagoon's basin has had an important effect on the water level in the city.

3.4.3.1.1 Accelerated Subsidence of Venice

Industry began in Venice during the 1920s at Porto Marghera, near Mestre. During the 1930s, electrical pumps were brought into Marghera to draw water from the subsoil for industry, irrigation, and Venice's municipal water. This accelerated the rate of subsidence in Venice from 1.27 cm in 10 years to 5.08 cm in 10 years. Although there were other geological changes contributing to the sinking of Venice, this pumping of water from the subsoil was the main cause. The government passed national laws to help prevent Venice from sinking further, which included forbidding the removal of water from the subsoil for industrial purposes. After the laws were passed, the accelerated subsidence ceased and now continues at its natural rate of 1.27 cm every 10 years[5]. The effects of subsidence combined with the eustatism of the Lagoon are causing a gradual increase in the average water level in Venice.

3.4.3.1.2 Global Warming and Eustatism of Venice

The average sea level of the Earth has slowly been increasing as a result of the greenhouse effect, and this is known as eustatism. This rise in sea level will in turn affect the water level of the canals in Venice.

The climate of the Earth has been changing as a result of human activities such as the combustion of fossil fuels. Since the beginning of the industrial revolution, the composition of the Earth's atmosphere has been altered significantly. The concentration of certain compounds,

---

[3] The process of land settling.

[4] The rising of the water level.

[5] Lane, Frederick. Venice: A Maritime Republic.

primarily carbon dioxide, has increased, causing the Earth's atmosphere to trap more heat, thus causing global temperatures to rise. This is known as the greenhouse effect.[6]

The greenhouse effect has caused many changes in the atmosphere as well as on the Earth's surface. The consequences of these changes in global conditions are numerous. The trapping of heat has caused the melting of glaciers, thus raising the amount of water in the oceans. As a result, the global sea level has risen, causing ocean shores to erode.[7] The change in sea level increases the vulnerability of coastal areas to flooding. Coastal marshes and swamps are most vulnerable to the rising sea level because they are mostly within a few feet of the sea. As the sea rises, it causes the outer boundary of these wetlands to erode, thus forming new wetlands and flooding previously dry areas. Global warming is expected to raise the sea level an additional 15 cm by the year 2050 and 34 cm by the year 2100. By the year 2100, changes in the climate are likely to increase the rate of the rise in sea level by 4.2 cm per year.[8]

3.5 Tide Forecasting

Predicting the tides involves many variables. Long term forecasting takes into account lunar and solar effects, as well as permanent morphological factors. Short term forecasting also includes meteorological conditions. Being able to predict the tides provides scientists with much information and allows them to prevent many problems associated with flooding caused by unusually high tides.

---

[6] U.S. Environmental Protection Agency, http://www.epa.gov/globalwarming/impacts/coastal/index.html.
[7] U.S. Environmental Protection Agency, http://www.epa.gov/globalwarming/impacts/coastal/index.html.
[8] U.S. Environmental Protection Agency, http://www.epa.gov/globalwarming/impacts/coastal/index.html.

3.5.1 Centro Previsioni e Segnalazioni Maree

Venice frequently experiences higher than normal tides from September to April. During these high tides, or *acque alte*, the water level can rise enough to flood the ground floors of buildings in the lowest parts of Venice. This can cause extensive damage to homes and businesses in those areas. In order to help the citizens of Venice prepare for such floods, the Communal Administration created the Tide Forecasting and Warning Center (*Il Centro Previsioni e Segnalazioni Maree).* The Center has three main purposes: to acquire data regarding the tides, to forecast tides, and to warn the citizens of Venice when the tide is expected to rise to damaging levels.

3.5.2 Long Range Forecasting

Tide charts predicting the arrival times and expected levels of the tides are based on the phases of the lunar and solar cycles (Figure 4). Scientists in Venice use 8 harmonic constants (Figure 8) to produce tide forecasts on a yearly basis. Each constant reflects a predictable long-range astronomical or morphological factor that affects the tides of Venice.[9] These predictions provide the expected times and levels of the tides but are not very accurate because they do not take into account the local meteorological conditions.

---

[9] *Centro Previsioni e Segnalazioni Maree* *Previsioni delle altezze di marea per il bacino di San Marco e delle velocità di corrente per il Canal Porto di Lido - Laguna di Venezia,* p. 6.

Constanti Armoniche Delle Maree

Punta Della Salute (Venezia)

	M_2	S_2	N_2	K_2	K_1	O_1	P_1	S_1
A (cm)	24.2	14.3	3.9	4.2	17.4	5.2	5.9	1.5
N	308°	317°	309°	313°	86°	76°	84°	270°

Latitudine 45° 25' 51" N
Longitudine Greenwich 12° 20' 15" E

Figure 8: Harmonic constants used to predict tides in Venice

3.5.3 Short Range Forecasting

Il Centro Previsioni e Segnalazioni Maree uses a network of meteorological stations throughout the Mediterranean and Adriatic Seas to provide daily short-term forecasts of the tides coming into Venice. Because these predictions can take into account the present weather conditions as well as the long range astronomical and morphological effects, they are more accurate than the long-term tide forecasts (Figure 9). This figure shows the forecast for the week of June 25th, 1999 and contains the astronomical forecast shown by the solid line as well as the updated meteorological corrections shown by the dotted line.[10]

---

[10] *Commune Di Venezia, Centro Previsioni e Segnalazioni Maree.* Venice, 4090 San Marco, 1999.

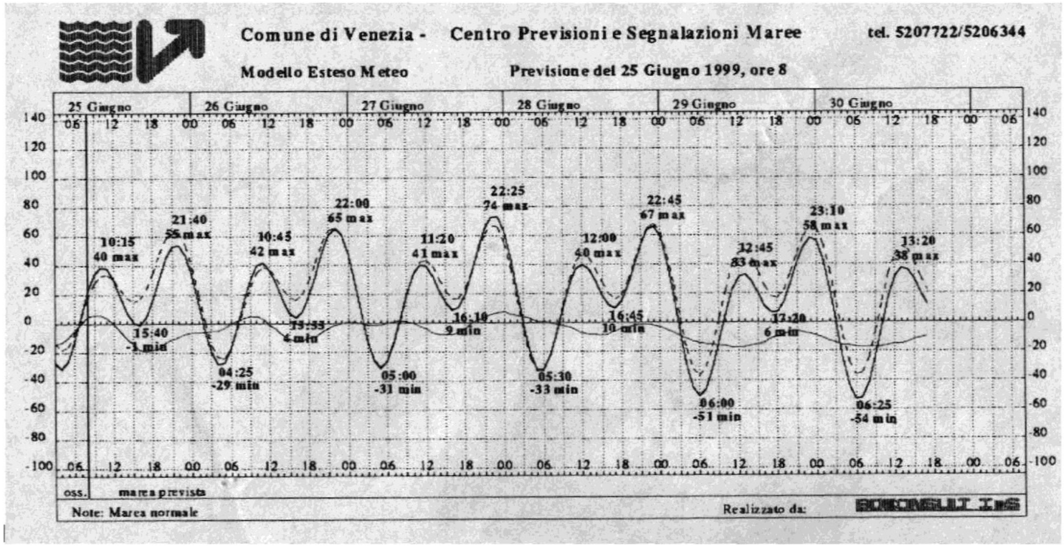


Figure 9: The meteorological forecast of Venice for the week of June 25th, 1999

3.5.4 Applications of Forecasting

Because the tides structure the Venetian way of life, the prediction of tides allows the residents of Venice to not only prepare for flooding but to schedule their daily lives as well. The prediction of tides also gives the city the ability to prevent problems associated with the high tides.

3.5.4.1 Warnings

The *Centro Previsioni e Segnalazioni Maree* uses the ability of forecasting the tides to provide advanced warnings to the city when dangerously high tides are predicted. When the tide is predicted to reach 110 cm above the mareographic zero, the *Centro* sounds 16 sirens stationed throughout Venice to warn residents that high tides will be arriving. The *Centro* also sends faxes and makes phone calls to the public works agencies, giving them an even more advanced warning about both high and low tides. Since the tides can flood businesses and residences this warning system allows individuals and agencies to prepare for flooding.

3.5.4.2 Flood Gates

One way Venice is attempting to protect itself from damaging water levels is to design flood gates that will regulate the rising and falling of tides at the three entrances to the Lagoon. These flood gates will rise from the floor of the entrance channels to the Lagoon and stop the water from entering. However, it takes the gates roughly 60 minutes to rise, making accurate tide forecasting necessary. Since scientists are able to predict when the high tides will occur, it gives Venice the opportunity of raising the flood gates and preventing the tide from flooding the city. These flood gates are still under consideration for use because of the major effects they will have on the water flow and ecology of the entire Lagoon.

3.5.4.3 Field Studies

Being able to predict the tides also allows for the planning of canal studies, such as surveys of canal walls and sewer outlets and hydrodynamic characteristics, whose data collection times are dictated by the tidal cycle. Studies such as these are very important to the safeguarding of Venice and will allow experts to keep Venice a livable city.

3.6 Previous Studies of Canal Flows

In order to gain more knowledge about the methods for collecting data on water velocities in Venetian canals, past canal studies that were conducted during the 20th century were reviewed. These include independent studies as well as previous WPI student projects. A key point to consider is that none of the independent studies used canal segments as the unit of measurement; rather, they involved studies of entire canals.

3.6.1 Paluello (1900)

In 1900, a hygienist named Paluello attempted to determine whether the bridge that connects Venice to the mainland adversely affected the ability of the canals to function as the city's sewage system. It is not certain whether he answered his original question, but he did end up with an interesting analysis of the hydrodynamic flow of the Venetian canals. Paluello found that for the most part, water flowed west through the canals during incoming tides, and east during outgoing tides. More importantly, he qualitatively estimated which canals provided the most water to the city.

According to his report, the three canals which are the primary water suppliers are the *Canale della Giudecca* for southern Venice, the *Fondamente Nuove* for northern Venice, and the *Canal Grande* for central Venice. Paluello observed 160 canals, and found the flows to be between 12 and 20 cm/s for north/south canals. He also found 12 canals that appeared to be stagnant; that is, they had flows less than 3 cm/s. Paluello decided that anything less than 5 cm/s would be hygienically ineffective, so by this criteria there were 27 to 32 canals not capable of significant sewage removal.[11] Since Paluello only qualitatively assessed flow velocities, his report gives only a rough estimate of the actual movement of water through the canals.

3.6.2 Fabris (1937)

In 1937, Cesare Fabris published a classification system based on three types of canals. First order canals, the *Canale della Giudecca, Fondamente Nuove,* and the *Canal Grande* had been found by Paluello to carry most of the water in the city to the lesser canals,which generally flowed outward from the *Canal Grande* during ascending tides, and inwards towards it during descending tides. Second order canals were those connecting two points on the *Canal Grande*, and their flows could be predicted from elementary fluid theories. Third order canals were those

---

[11] Paluello, Carlo (1900), *Note igieniche sul progettato ponte lagunare-con particolare riguardo alla malaria,*Tipolit-Ferrari, Venezia, 1900.

that connected two points near, but not on, the *Canal Grande*. They were found by Fabris to have negligible flows.[12] Fabris was more concerned with the direction of water flow and therefore did not measure the velocity of the water as it moved through the canals.

3.6.3 Dorigo (1966)

In 1966, Livio Dorigo, director of the *Ufficio Mareografico del Magistrato alle Acque*, published data from a study performed between May 3 and 5, 1962. He catalogued the information from the first ever simultaneous recording of velocities and directions of currents on almost the entire Venetian canal network. These data were then correlated with readings from the existing tide charts, and the results helped to verify Paluello's previous findings (Figure 10).[13] Dorigo's study was quantitative, however he took general flow readings instead of determining the maximum velocity of the water.

---

[12] Fabris, C. *La Marea nei Canali di Venezia*, pp. 187-188, (1937).

[13] Dorigo, Livio. *Rilievi Contemporanei di velocità di marea nei canali della Giudecca, Fondamente Nuove, Canal Grande ed alcuni rii interni della città*, Vol III. (1966).

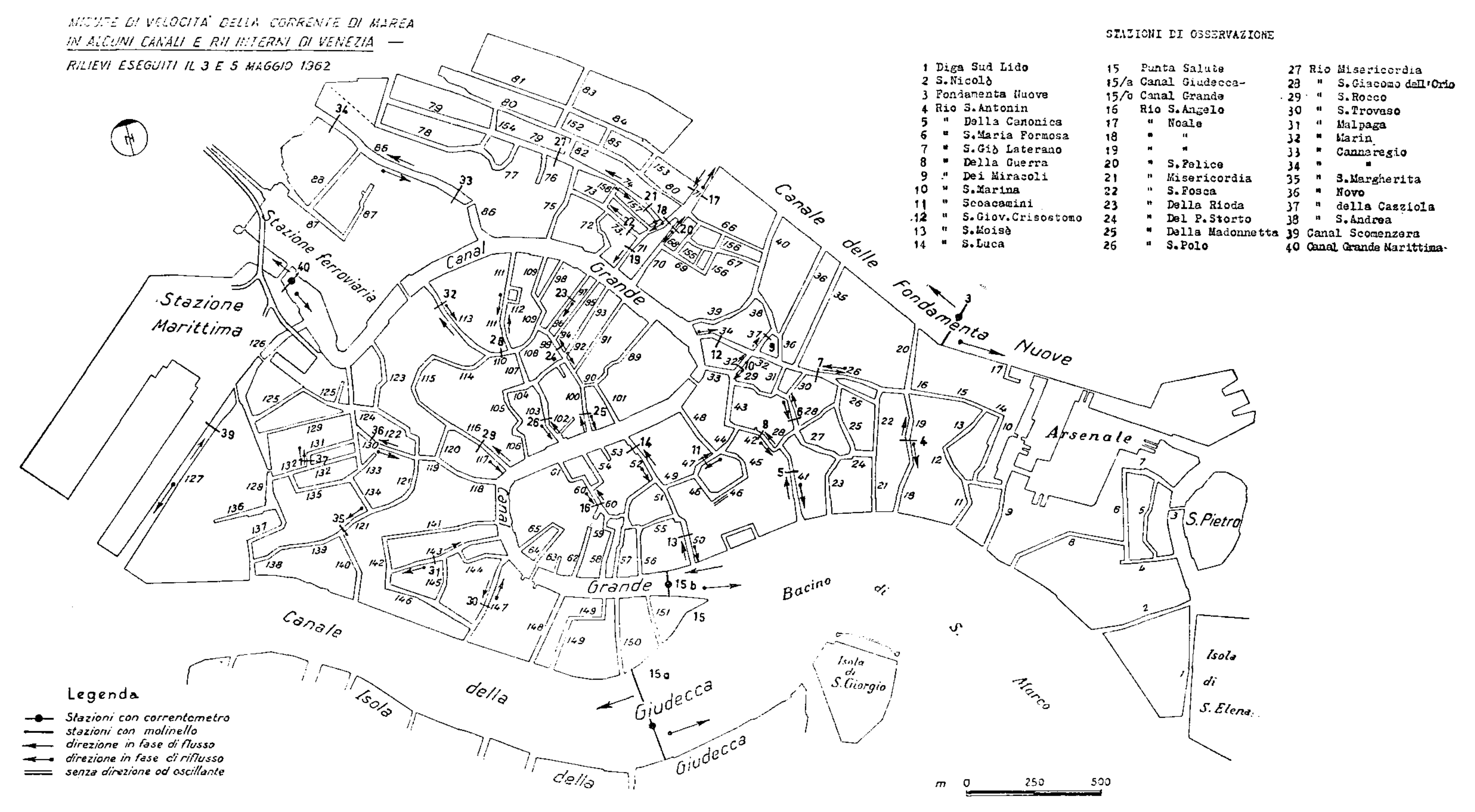


Figure 10: Map showing the data compiled by Dorigo

3.6.4 Alberotanza and Dazzi (1970)

On June 3, 1970, an Argentinean painter dropped 20 kg of emerald green dye in the *Canal Grande* as part of a performance for the Biennale, the Venetian modern art festival. Two scientists, Alberotanza and Dazzi, took advantage of the opportunity to track the dye's movement along the Venetian canals. They found that water from the *Canal Grande* that ended up in the *Piazzale Roma* reached its destination faster by going through the secondary canals than by travelling only along the *Canal Grande*. They also found that the *Fondamente Nuove* actually provides very little water to the inner canals, contrary to what Paluello had said 70 years earlier.[14] This study showed which canals provided the fastest routes for the water to flow through the city. However, it did not track the water's velocity through individual canal segments but rather focused on how quickly the water reached its final destination. Also, it can not be verified that the dye traveled with the main current, and therefore the value of the results provided by this study is somewhat doubtful.

3.6.5 Past WPI Hydrodynamic Studies

To date, WPI students are one of the largest collectors of detailed information regarding the Venetian canal system. Students have taken velocity measurements during the new moon, full moon, and quarter moon phases. During a full tide cycle, five specific measurement times were used: high tide, halfway between high and low tide, low tide, halfway between low and high tide, and high tide again (Figure 11). Their data proved that the maximum velocity occurred at the halfway points between high and low tides. Since we were only concerned with determining the maximum velocities of the canal segments, we only made measurements at those

---

[14] Alberotanza, L. e Dazzi, R. *Descrizione del Percorso all' Interno di Venezia Seguito da una Macchia di Colorante Immesso in Canal Grande, p. 4 (1970).*

times. However, not every canal segment has been measured with respect to velocity. The velocity data that has been collected since 1991 (Appendix D) is included in the database that we completed (Appendix E). Here is a summary of the past hydrodynamic studies done by previous WPI project teams.

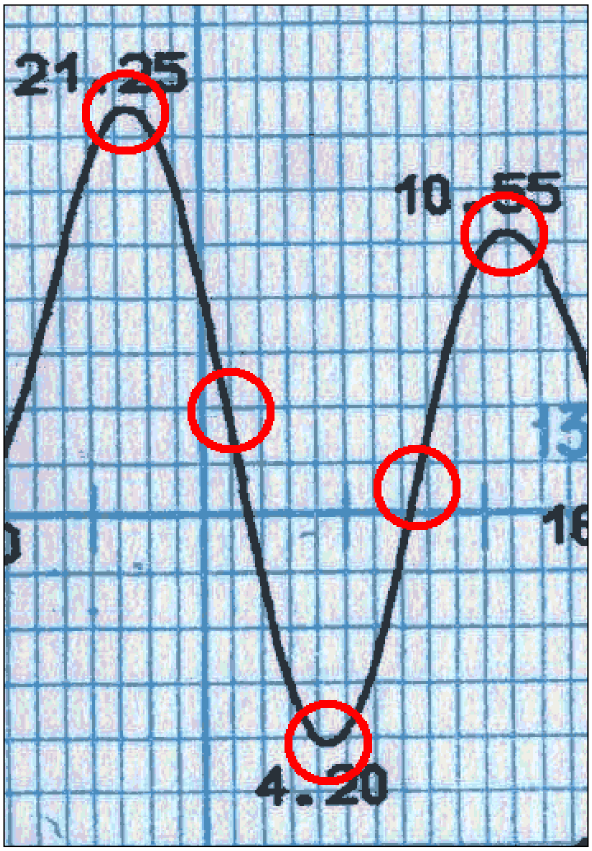


Figure 11: Tide cycle measurement times used by past WPI projects

A Hygienic, Dynamic, and Static Study of the Canals of Venice, Italy (C'90)

This WPI project team was the first to deal with the flow characteristics of the Venetian canals. They studied four canals in *Dorsoduro* at the northern end of the Grand Canal, set the standards for taking flow measurements, and devised methods for archiving results in dBASE IV and Lotus 123. Their measurements were inaccurate, however, due to the fact that they used a cork as a flotation device, which traveled with the surface water only, and was highly susceptible to the effects of wind and boat traffic.

The Study of Tide Flows, Mud Buildup, Boat Traffic, and Structural Damage on the Cannaregio Canal Subsystem (D'91)

The students in this WPI project team studied the flow in the *Cannaregio sestiere*, covering a greater area than the previous WPI project. It introduced the first accurate flotation device which measures the flow at roughly one-third the depth and in the middle of the width of the canal. The project team also used MapInfo in an effort to link the measured data to maps of Venice, and reworked the canal segment naming system.

A Static and Dynamic Study of the Canals of Venice, Italy (C'92)

This WPI project team studied the static and dynamic characteristics of the canals in *Santa Croce* and *San Polo.*. They realized, however, that for the canals to be fully characterized, separate tasks would have to be done by future project teams.

A Topological and Hydro-Dynamics Study of the Canals in the San Marco (D'92)

The members of this WPI project group took velocity measurements in the *San Marco sestiere* and they improved the lag time calculations by taking readings from the public monitor in *Piazza San Marco* that took into account current meteorological effects.

A Topological/Hydro-Dynamics Study and Geographical Information System of the Canals in the Castello Area (E'92)

In this WPI project, the canals of the *Castello sestiere* were studied. The group created customized databases with a software program dBASE IV that were then used by subsequent WPI project teams until the introduction of MSAccess.

Chapter 4 – Literature Review

The following literature was used to gather the background information found in Chapter 3, Background.

Annual Activities Report, UNESCO Venice Office, 1997.

This brochure was very informative about our sponsor UNESCO-ROSTE, and the many tasks it performs. It went into detail as far as the types of project work they have completed and are currently doing, and displays how their budget is formed. In general, it describes why ROSTE is an integral part of the education and technical aspects of Venice.

A Comprehensive Review of the Worcester Polytechnic Institute Venice Canal Studies. (D'93).

This past WPI project served as a guideline to help determine which information should be included in our background, literature review and the methodology. It pointed out the basic characteristics of the canal system and what has been studied up to 1993.

"Orbits," Nick Strobel, Internet, World Wide Web, http://www.bc.kern.cc.ca.us/programs/sea/Astronomy/gravappl/gravapplb.htm, April 4, 1999.

The web site, designed by Nick Strobel from Bakersfield College in California, describes the forces involved in planetary motion. He discusses how the gravitational pull on the Earth, moon, and sun coincide to produce tides. Information about the physical natures of tide formation and how it affects the movement of the Earth and moon was given. Also in the text was a description of the cycles of the moon and how they relate to the sun in tide formation.

"Our Restless Tides," Chapter Three, Center for Operational Oceanographic Products and Services, Internet, World Wide Web, http://www.opsd.nos.noaa.gov/restles3.html, April 11, 1999.

This web site provided detailed information on the main forces that produce tides, and gave several pictures to give a good visual understanding of how forces and pressure act on tides. It also helped in explaining the cycle and orbit of the Earth's moon and how it affects the formation of tides. This chapter explained how there is a certain tidal force envelope on the Earth and the two main forces causing tides, which include centrifugal and gravitational forces. Finally, it pointed out some of the other factors that influence tide formation such as astronomical occurrences.

"Our Restless Tides," Chapter Four, Center for Oceanographic Products and Services, Internet, World Wide Web, http://www.opsd.nos.noaa.gov/restles4.html, April 11, 1999.

This is a subset to the previous web site listed, where the content is focused more on specific tides at particular points of the year that consist of neap and spring tides. It explains the relationship between the moon and sun and their positions. It also points out that orbits of the sun and moon are not circular, so at certain times in their orbits, tides are stronger or weaker due to the change in their distance from the Earth.

"Our Restless Tides," Chapter Five, Center for Oceanographic Products and Services, Internet, World Wide Web, http://www.opsd.nos.noaa.gov/restles5.html, April 11, 1999.

Another division of the web site "Our Restless Tides", this explains the outside influences that affect the arrival of tides. This source points out some of the factors that may contribute to the inaccuracies of tide tables. Some of these contributing aspects are ocean depths, various winds, sea floor friction and land formations. The author points out how the tidal day was established to be 50 minutes longer than the regular day due to lunar retardation.

"MEDEX Winds," Naval Research Laboratory, Internet, World Wide Web, http://www.nrlmry.navy.mil/~medex/tutorial/medex/winds/wind_all.html, April 12, 1999.

This web site gave accurate information about two major winds in the Adriatic Sea, the Bora and the Sirocco. It explained how each wind develops, the regions where it formed, and what kind of effects it has on the Adriatic Sea and adjacent areas. Also included in the site were several maps that pointed out the directions of the winds.

Development of a Computerized Decision Support System for the Scheduled Maintenance of the Inner Canals of Venice (July, 1997)

This WPI project provided us with a description of what the data that we will be collecting will ultimately lead to, a decision support system that utilizes all the Venetian data. It also described the data that had been collected up to this point from all of the projects.

Analysis of Sewer Holes and Canal Wall Damage in Venice, Italy (July, 1998), Venice E99 Materials CD-ROM.

This project focused on the canals of Venice, and it provided us with information about them in the form of Access databases and MapInfo layers. It also gave information useful in other non project-specific background areas.

"EPA Global Warming: Impacts –Coastal," Environmental Protection Agency, Internet, World Wide Web, http://www.epa.gov/globalwarming/impacts/coastal/index.html, April 15, 1999.

The web site of the Environmental Protection Agency is very useful for finding information about global warming. It has many reports that were written by teams of scientists from all over the world discussing and forecasting the effects of global warming on water sources, agriculture, and the health of people and animals.

Venice: A Maritime Republic. Lane, Frederic (Baltimore: Johns Hopkins University, 1973)

This book gives a thorough explanation of the history of Venice from its beginning through recent times. Of particular use was the last chapter in the book, which discussed the situation of modern Venice in regards to its future direction and its plans for dealing with canal related problems.

Chapter 5 – Methodology

To characterize the hydrodynamics of the canal system of Venice, it was necessary to obtain maximum velocity measurements for canals that had not been previously measured or for which there was unreliable data. This chapter presents the methods used to measure the flow velocity characteristics of the Venetian canal system. Section 5.1 discusses the system with which we acquired our data. Section 5.2 details the scheduling of the measurement times used for collecting data. The criteria for determining which canal segments were to be measured and where velocity data was insufficient are explained in section 5.3. Finally, section 5.4 fully describes the organization of our data through the use of Microsoft Access.

5.1 Measuring Flow Velocities

In obtaining our data it was necessary to keep the measurement procedures and choices of sites consistent with those used by past WPI project groups. This was so that our data would be comparable to data obtained in past studies.

5.1.1 General Measurement Procedure

To measure the velocity of the tide, we timed how long it took a flotation device (section 5.1.3) to travel a predetermined distance that was marked off using landmarks, such as the distance from a pole to a wall. First, a preliminary throw was made to determine the direction of the current. Once the direction was known the flotation device was thrown slightly ahead of the first landmark to ensure that the device was moving at the same speed as the water when it passed the starting line. The stopwatch was started when the flotation device passed the first landmark, and stopped when it reached the second (Figure 12).

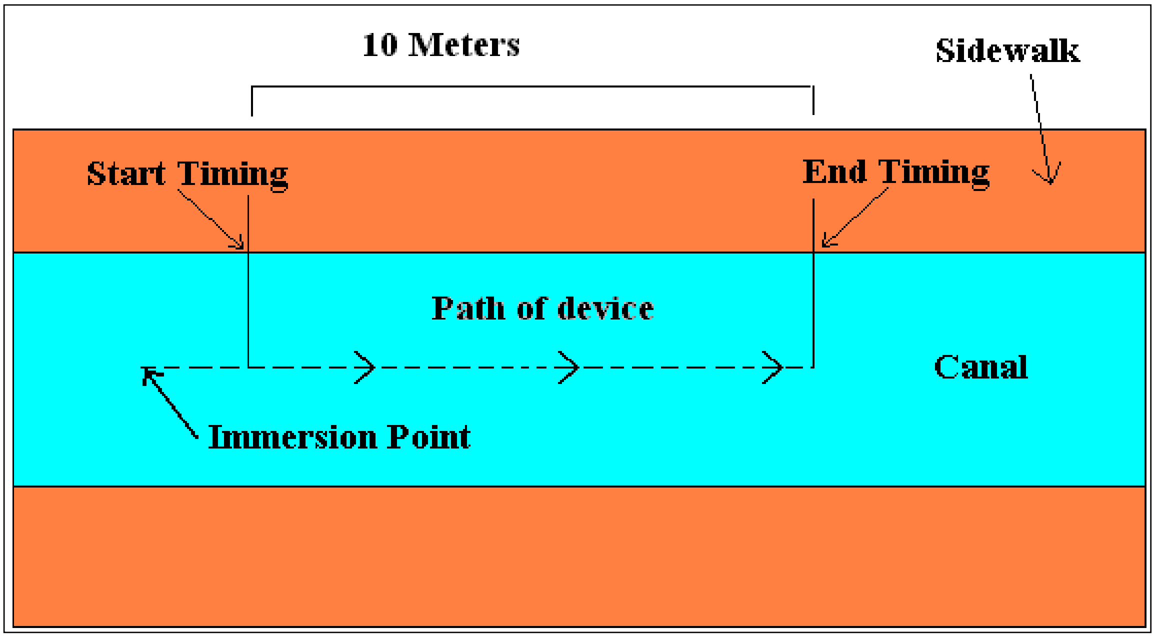


Figure 12: Procedure for obtaining measurements

This measurement procedure was repeated three times to detect any anomalous readings. We then moved to the next canal segment to be measured during that time period and repeated the process. After the measurer made initial measurements for each of designated canal segments, he then rotated through them again until the velocities consistently decreased.

5.1.2 Choosing Measurement Locations

Measuring the velocity of the water in different parts of a canal segment can result in inconsistent data because of variations in width, depth, and topology. Previous project teams compared data collected using 10 m and 5 m stretches and found that using 10 m stretches resulted in better precision. In order to comply with previous procedures, we used measurement lengths of 10 m where possible.

A standard hydrodynamic principle states that the water flow through an open channel is fastest halfway between the canal banks and at one-third of the depth below the surface. This is because water flowing along the banks and the bottom is affected by friction, and wind can affect the flow of the surface water (Figure 13). We measured at the middle of the length of the canal segment so that the measurements taken were the least affected by the disturbances caused by the intersecting canals.

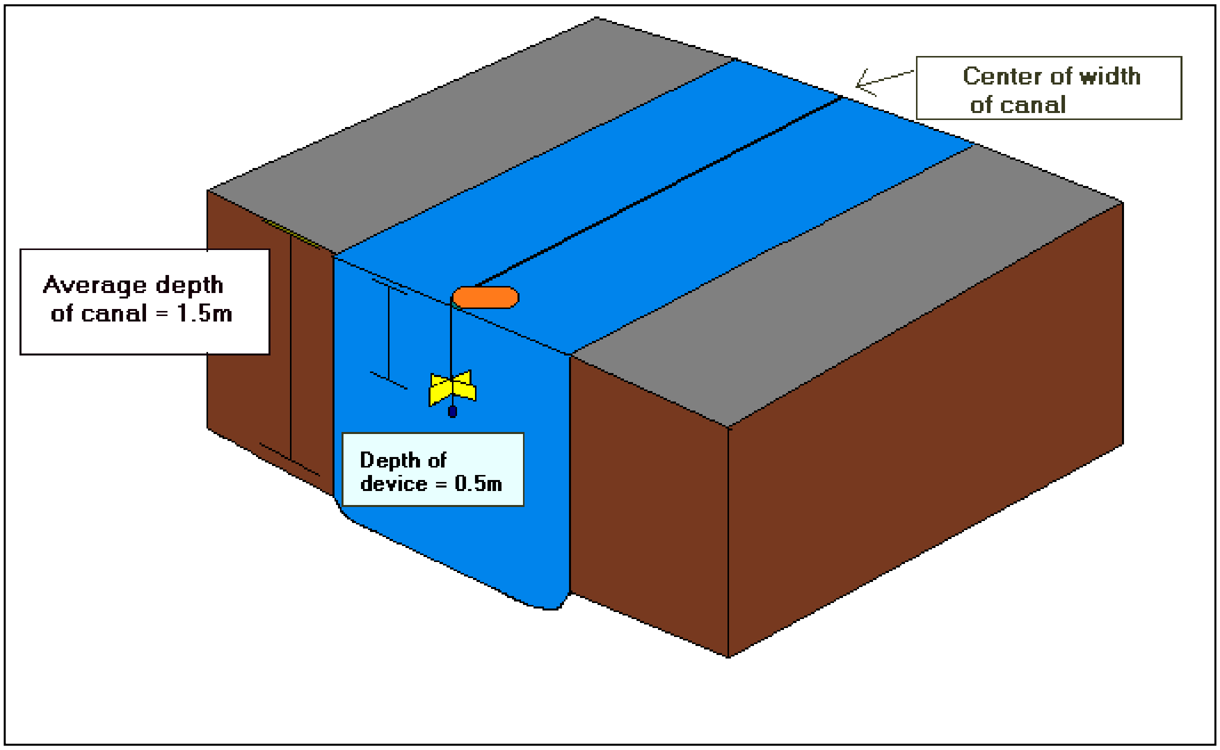


Figure 13: Cross section of a canal showing the position of the flotation device

5.1.3 Measuring Instrument

As explained later in section 5.3.1.1, the use of inadequate instrumentation can result in inaccurate, and therefore useless data. We used a flotation device that had been used in previous WPI projects (Figure 14). This device gives precise results because it is designed to travel with the maximum flow of the canal and not just the flow of the surface water. The instrument consists of a bottle used for buoyancy and two aluminum blades with a weight attached beneath them. The bottle is small in order to reduce the effects of the wind, and painted in a fluorescent color so that it could be seen in the dark. The weight kept the device perpendicular to the surface of the water and at a depth of 50 cm. Further details of the device and its construction can be found in Appendix F.

Figure 14: Flotation device used for data collection

5.2 Scheduling Flow Measurements

Our measurement times were scheduled during full and new moon phases, since these cause the greatest change in water velocities between the incoming and outgoing tides. In order to obtain the maximum velocity of the water, we needed to make the flow measurements at specific times. From the daily tide charts provided by the *Centro Previsioni e Segnalazioni Maree,* we were able to find the times which were the midpoint between the high and low tides (Figure 15). We collected data at these times because that is when the water velocity is at the maximum as explained in section 3.6.5.

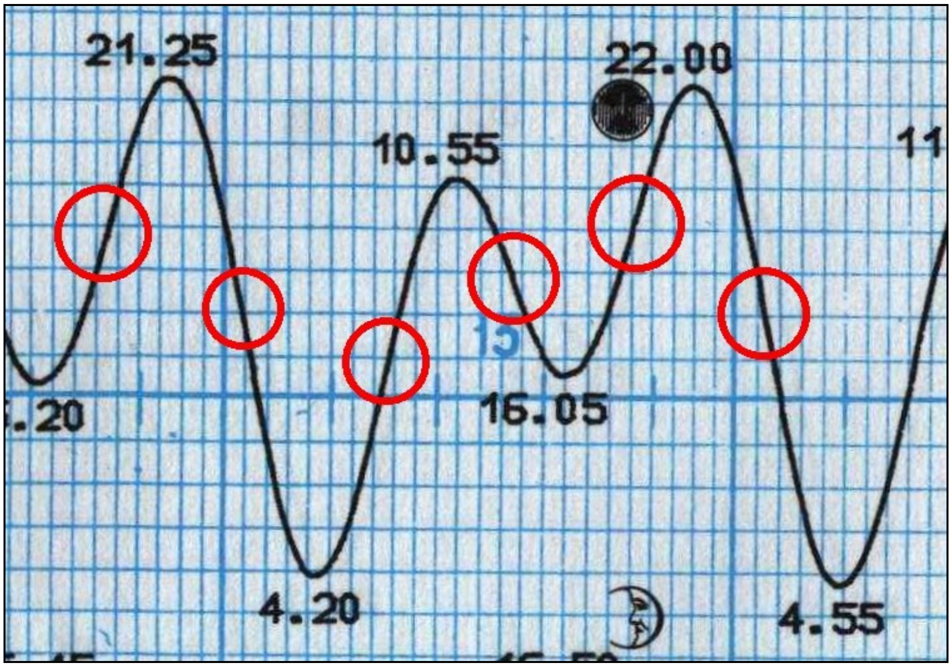


Figure 15: Example of predicted times of maximum flow velocity during a *sizigia*

5.2.1 Lag Times

Because the water enters Venice from the southeast, there is a time delay from when the water enters the southeastern canals to when it reaches the northernmost canals. Even though this would indicate that the measurements could be taken later than the estimated midpoint between high and low tides, we determined from making sample measurements that all of the canal segments experience different lag times. Because of this, we established that measuring one hour before the expected maximum velocity would ensure that we would not miss the fastest flow.

5.2.2 Daily Schedule

Because the new and full moon phases occurred a total of three times during our period of field work, it was logistically impossible for us to take measurements for all of our targeted canal segments during each of those 24-hour periods. Therefore, we extended the time for taking measurements to 48 hours before, and 48 hours after the new and full moon. Appendix C contains the daily schedule we used to obtain measurements.

5.2.3 Off Day Scheduling

Since we were dependent on the tide cycle, we were only able to collect data during four days every other week. This means that we only had 12 days to collect data. During the days we were not measuring, we determined which stretches of the unmeasured canal sections would give us the most accurate data and took digital images of the stretches we had already measured. We also spent these off days entering the collected data into the database, analyzing the results, and writing this report.

5.3 Area of Study

Before data collection began, it was necessary to determine which of the previous data were inaccurate or absent, to identify which segments should be targeted for our measurements.

5.3.1 Target Canals

Our project covered all canal segments that had not been previously measured or for which there were dubious data. We identified our target canals by analyzing the velocity results of previous WPI projects.

5.3.1.1 Unreliable Data

We determined that it was necessary to re-measure all of the canals where measurements had been taken before 1991. This is because the flotation device used before that time gave inaccurate results. The 1990 WPI project team measured the velocity of the current with corks, which could not provide accurate results because they were more susceptible than the device used by later team to the effects of the wind and traffic on the surface of the water. Because the measurement most representative of the flow of a canal is taken at one third its depth, and the corks used in 1990 traveled on the surface of the water, the data collected did not represent the true maximum velocity of the water, and were therefore unreliable.

5.3.1.2 Missing Data

Previous Venice WPI project teams did not collect velocity data for all canal segments in Venice. By analyzing Ing. Fabio Carrera's report we determined where velocity measurements had not been made (Figure 16). The data for previously measured canal segments are found in Appendix D. We collected data for these canal segments to ensure that water velocity data was collected for as many canal segments as possible.

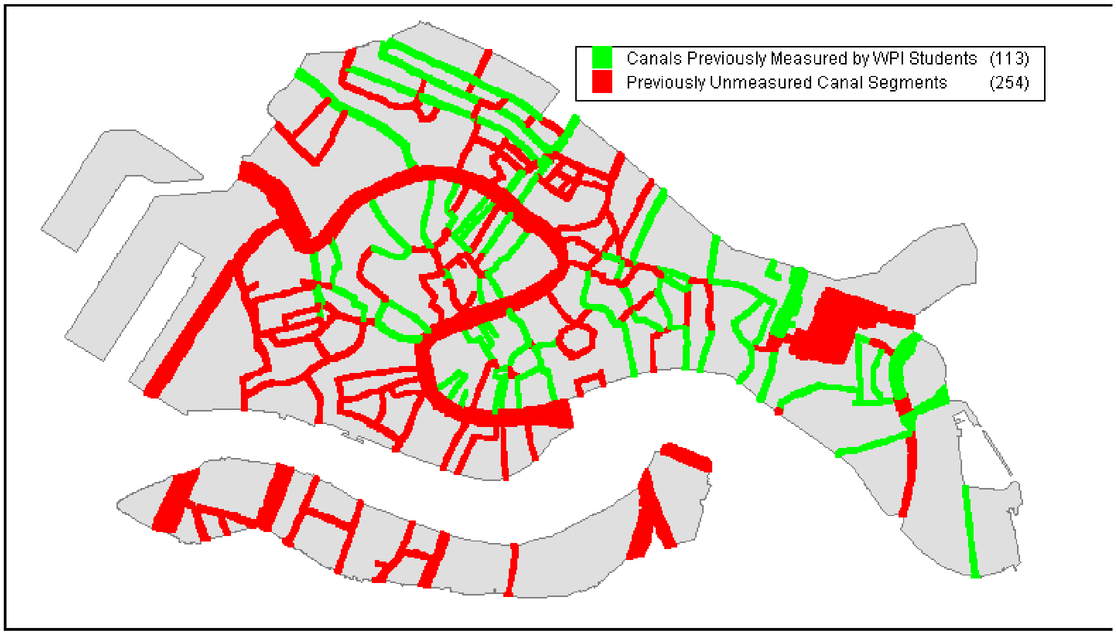


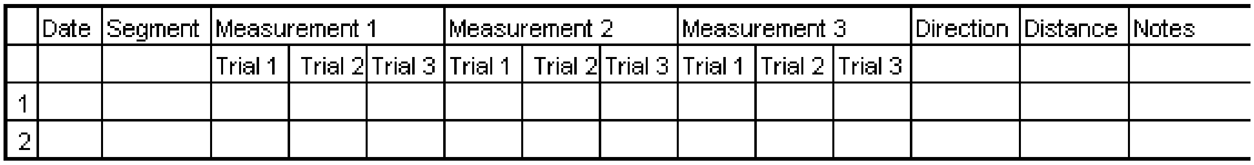
Figure 16: Map showing canal segments measured by previous WPI project teams

5.4 Recording and Archiving Data

The data that we collected are part of a large database that is intended to completely characterize the static and hydrodynamic properties of the canals. The data obtained in this study were combined with the database that had been previously created to compile all of the information from past WPI projects involving measurements of canal flows. We filled in missing velocity measurements and updated old, inaccurate measurements. The data tables are all contained in a Microsoft Access file called IDRODYNAMICAV4.MDB that can be found in the CD that accompanies this report.

5.4.1 Parameters Collected

The actual data collected were placed in a field form with the column headings shown in Figure 17. All field forms used are included in Appendix G. When taking measurements, we first filled in the information regarding date, segment name, direction of water flow, and distance measured. We then recorded the time of day each trial was made using 24-hour military time on line 1 and the length of time it took the device to travel the predetermined distance on line 2. At the end of the measurement period we filled in any notes regarding boat traffic, wind, or other possible influences on the measurement accuracy.



	Date	Segment	Measurement 1			Measurement 2			Measurement 3			Direction	Distance	Notes
			Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3			
1														
2														

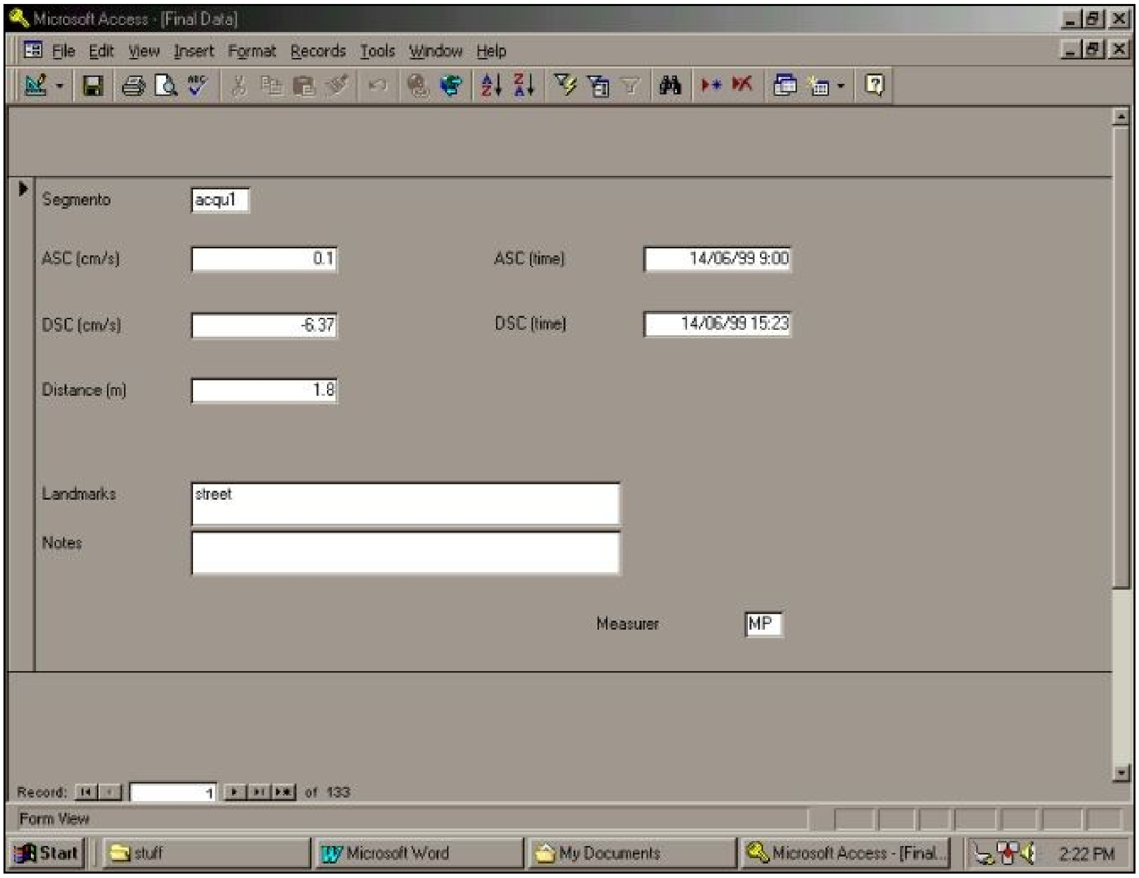
Figure 17: Field form used in data collection

5.4.2 Computerized Archival of Field Data

The database that we designed is made up of two tables. The Field Data Table contains the data that was recorded through the Data Entry Form, and the Image Recording Table contains the digital images of each canal segment as well as a MapInfo map of the measurement site in relation to the entire segment. MapInfo is a computer program that enabled us to make maps of Venice to present and analyze our data.

5.4.2.1 Data Entry Form

We used the Data Entry Form to input our collected data into the database (Figure 18). The form contains many fields: the canal segment code; the maximum velocity, time and date of measurement for the incoming tide; the maximum velocity, time and date of measurement for the outgoing tide; the distance measured; the landmarks used to identify the measurement stretch;



Segmento acqu1
ASC (cm/s) 0.1
ASC (time) 14/06/99 9:00
DSC (cm/s) -6.37
DSC (time) 14/06/99 15:23
Distance (m) 1.8
Landmarks street
Notes
Measurer MP
Record: 1 of 133

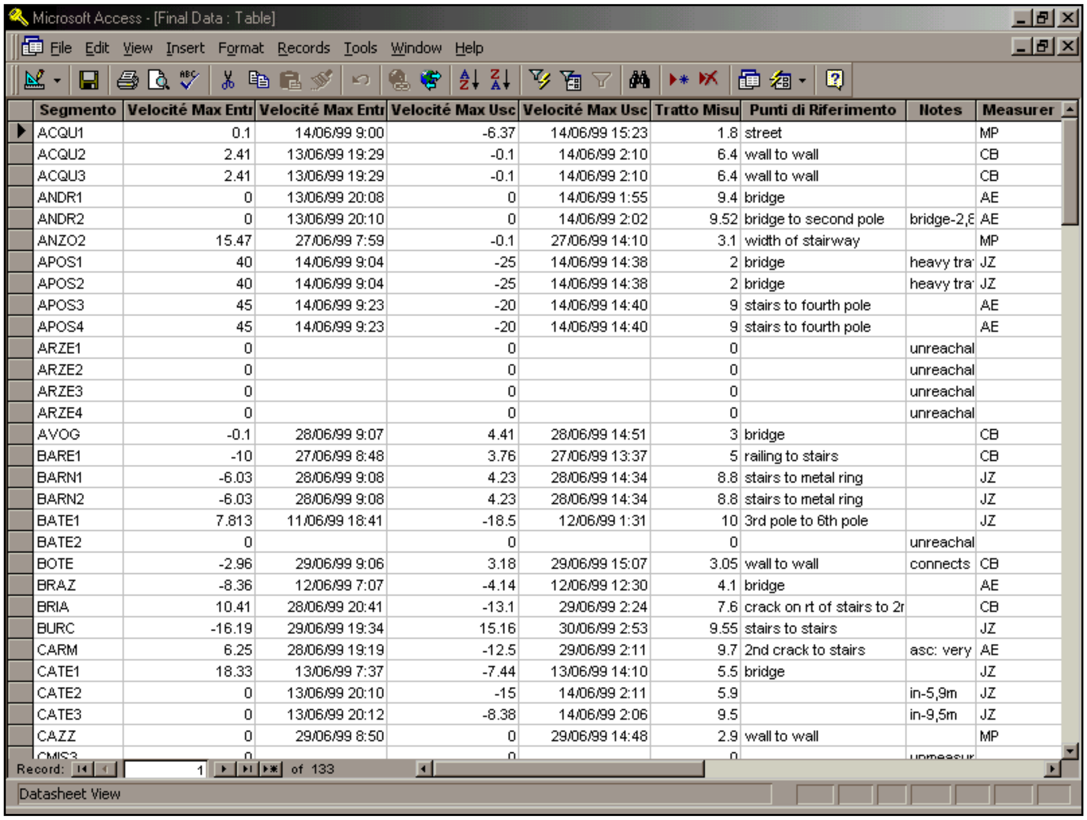
Figure 18: Screen capture of database entry form

the initials of the measurer; and notations of any conditions that may have occurred during the measurements that could have affected the data. All measurements were recorded in units of centimeters per second (cm/s).

The direction of the current was recorded when the measurements were made and designated North or South. When entering the data into the form, current travelling in a northerly direction was given a positive value, and current travelling in a southerly direction was given a negative sign. For the canals that flowed east and west, we determined which end of the canal segment was the northernmost, and assigned the sign of the velocity in the same way as for all the other canals. Appendix H contains the directional layout of all the canals.

5.4.2.2 Final Data Table

This table was the actual repository of all the information that was put into the Data Entry Form (Figure 19). It is arranged in alphabetical order by canal segment codes. The final data is contained in a table called "Final Data" in the Access file IDRODYNAMICAV4.MDB in the enclosed CD.

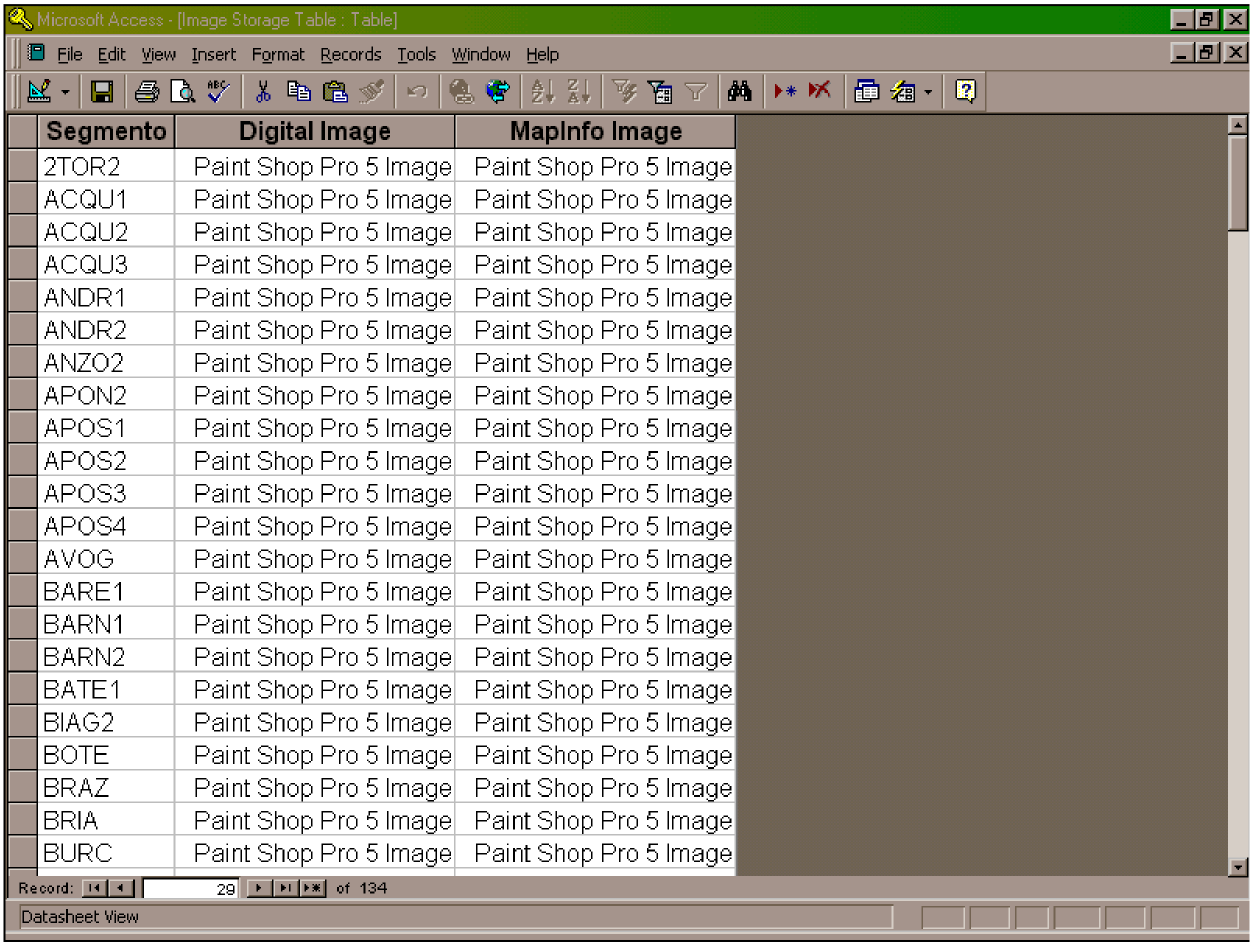


Segmento	Velocité Max Entr	Velocité Max Entr	Velocité Max Usc	Velocité Max Usc	Tratto Misu	Punti di Riferimento	Notes	Measurer
ACQU1	0.1	14/06/99 9:00	-6.37	14/06/99 15:23	1.8	street		MP
ACQU2	2.41	13/06/99 19:29	-0.1	14/06/99 2:10	6.4	wall to wall		CB
ACQU3	2.41	13/06/99 19:29	-0.1	14/06/99 2:10	6.4	wall to wall		CB
ANDR1	0	13/06/99 20:08	0	14/06/99 1:55	9.4	bridge		AE
ANDR2	0	13/06/99 20:10	0	14/06/99 2:02	9.52	bridge to second pole	bridge-2,	AE
ANZO2	15.47	27/06/99 7:59	-0.1	27/06/99 14:10	3.1	width of stairway		MP
APOS1	40	14/06/99 9:04	-25	14/06/99 14:38	2	bridge	heavy tra	JZ
APOS2	40	14/06/99 9:04	-25	14/06/99 14:38	2	bridge	heavy tra	JZ
APOS3	45	14/06/99 9:23	-20	14/06/99 14:40	9	stairs to fourth pole		AE
APOS4	45	14/06/99 9:23	-20	14/06/99 14:40	9	stairs to fourth pole		AE
ARZE1	0		0		0		unreachal	
ARZE2	0		0		0		unreachal	
ARZE3	0		0		0		unreachal	
ARZE4	0		0		0		unreachal	
AVOG	-0.1	28/06/99 9:07	4.41	28/06/99 14:51	3	bridge		CB
BARE1	-10	27/06/99 8:48	3.76	27/06/99 13:37	5	railing to stairs		CB
BARN1	-6.03	28/06/99 9:08	4.23	28/06/99 14:34	8.8	stairs to metal ring		JZ
BARN2	-6.03	28/06/99 9:08	4.23	28/06/99 14:34	8.8	stairs to metal ring		JZ
BATE1	7.813	11/06/99 18:41	-18.5	12/06/99 1:31	10	3rd pole to 6th pole		JZ
BATE2	0		0		0		unreachal	
BOTE	-2.96	29/06/99 9:06	3.18	29/06/99 15:07	3.05	wall to wall	connects	CB
BRAZ	-8.36	12/06/99 7:07	-4.14	12/06/99 12:30	4.1	bridge		AE
BRIA	10.41	28/06/99 20:41	-13.1	29/06/99 2:24	7.6	crack on rt of stairs to 2r		CB
BURC	-16.19	29/06/99 19:34	15.16	30/06/99 2:53	9.55	stairs to stairs		JZ
CARM	6.25	28/06/99 19:19	-12.5	29/06/99 2:11	9.7	2nd crack to stairs	asc: very	AE
CATE1	18.33	13/06/99 7:37	-7.44	13/06/99 14:10	5.5	bridge		JZ
CATE2	0	13/06/99 20:10	-15	14/06/99 2:11	5.9		in-5,9m	JZ
CATE3	0	13/06/99 20:12	-8.38	14/06/99 2:06	9.5		in-9,5m	JZ
CAZZ	0	29/06/99 8:50	0	29/06/99 14:48	2.9	wall to wall		MP
CMIS3	0		0		0		unmeasur	

Figure 19: Screen capture of a portion of the final data table

5.4.2.3 Image Storing Table

This table stores all of the digital images of measurement sites and the MapInfo windows that show where we took measurements along each canal segment (Figure 20). The digital images show the landmarks used for making measurements and the MapInfo window shows where the measurement sites were located on each canal segment. The images are contained in a table called Image Storing Table in the Access file *IDRODYNAMICAV4.MDB* in the enclosed CD.

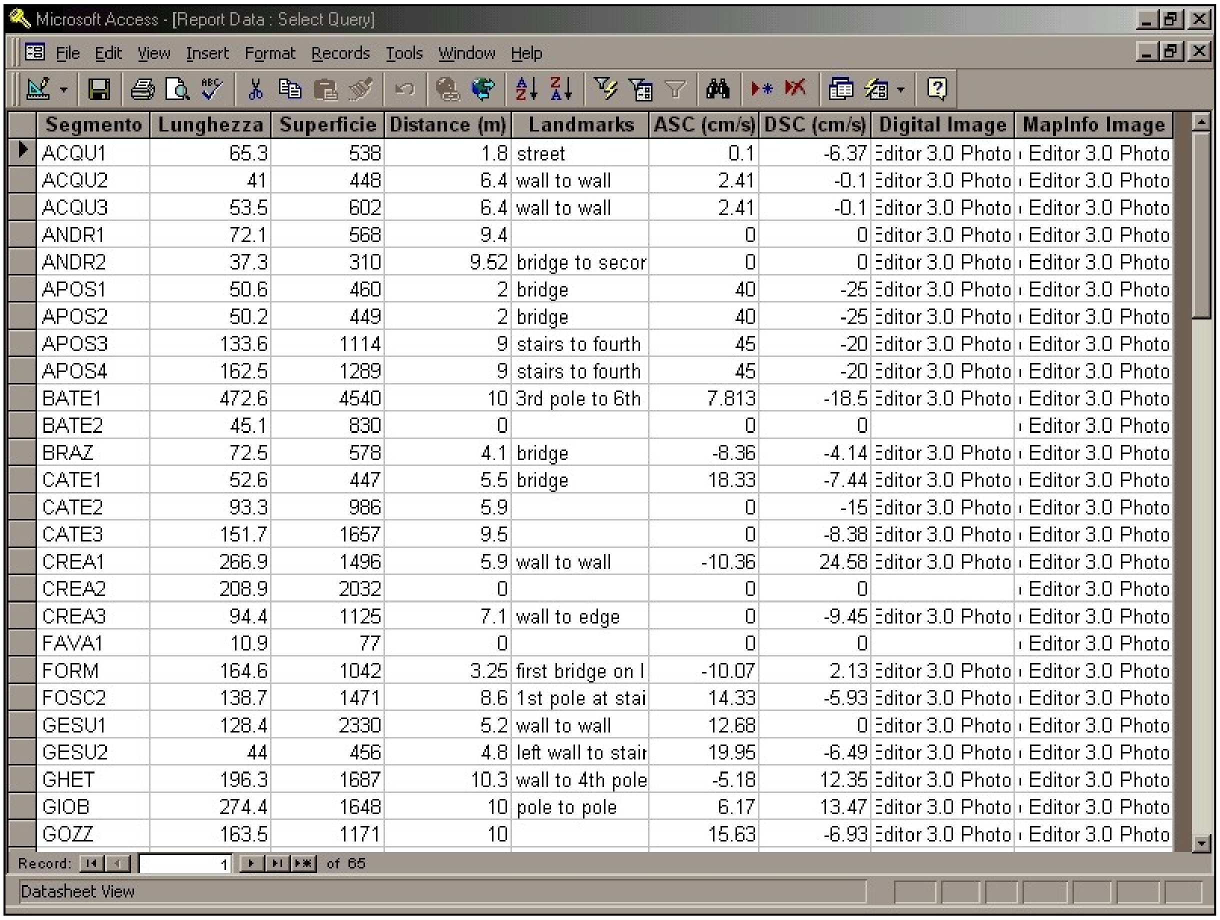


Segmento	Digital Image	MapInfo Image
2TOR2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
ACQU1	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
ACQU2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
ACQU3	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
ANDR1	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
ANDR2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
ANZO2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
APON2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
APOS1	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
APOS2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
APOS3	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
APOS4	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
AVOG	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BARE1	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BARN1	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BARN2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BATE1	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BIAG2	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BOTE	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BRAZ	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BRIA	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image
BURC	Paint Shop Pro 5 Image	Paint Shop Pro 5 Image

Figure 20: Screen capture of image storing table

5.4.3 Combined Data Query

This query (Figure 21) combines the data and the images with the dimensions of each canal segment, to be used in a final data catalogue.

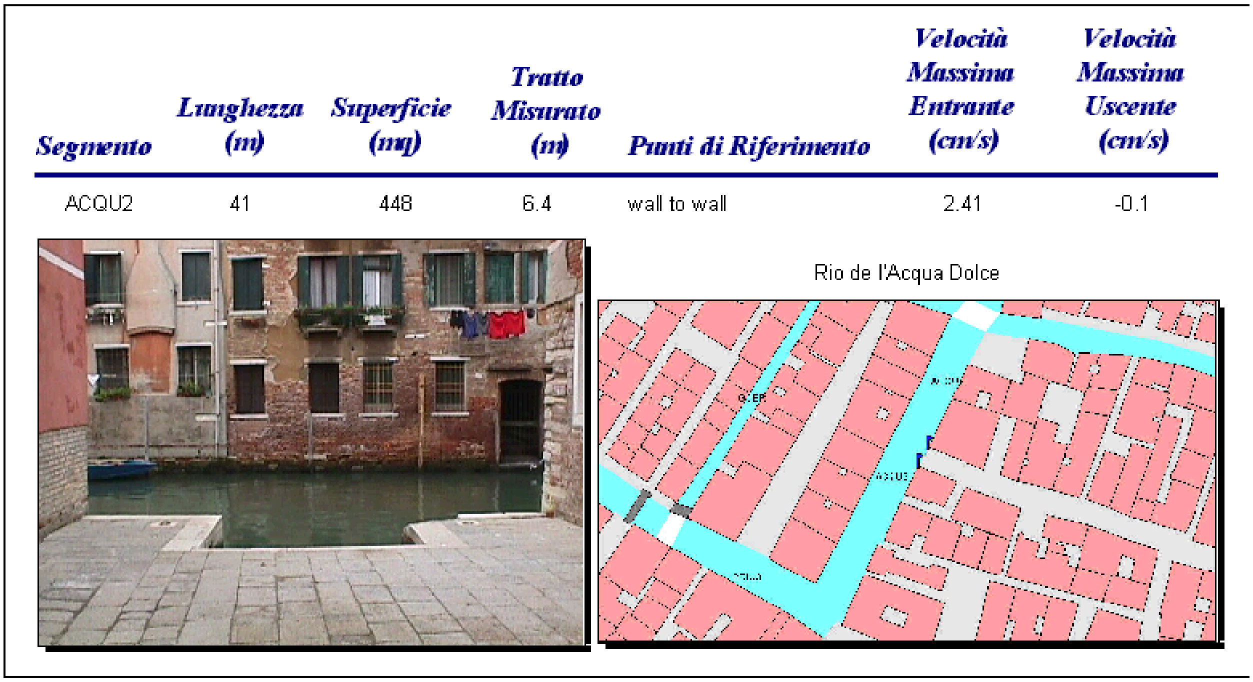


Segmento	Lunghezza	Superficie	Distance (m)	Landmarks	ASC (cm/s)	DSC (cm/s)	Digital Image	MapInfo Image
ACQU1	65.3	538	1.8	street	0.1	-6.37	Editor 3.0 Photo	Editor 3.0 Photo
ACQU2	41	448	6.4	wall to wall	2.41	-0.1	Editor 3.0 Photo	Editor 3.0 Photo
ACQU3	53.5	602	6.4	wall to wall	2.41	-0.1	Editor 3.0 Photo	Editor 3.0 Photo
ANDR1	72.1	568	9.4		0	0	Editor 3.0 Photo	Editor 3.0 Photo
ANDR2	37.3	310	9.52	bridge to secor	0	0	Editor 3.0 Photo	Editor 3.0 Photo
APOS1	50.6	460	2	bridge	40	-25	Editor 3.0 Photo	Editor 3.0 Photo
APOS2	50.2	449	2	bridge	40	-25	Editor 3.0 Photo	Editor 3.0 Photo
APOS3	133.6	1114	9	stairs to fourth	45	-20	Editor 3.0 Photo	Editor 3.0 Photo
APOS4	162.5	1289	9	stairs to fourth	45	-20	Editor 3.0 Photo	Editor 3.0 Photo
BATE1	472.6	4540	10	3rd pole to 6th	7.813	-18.5	Editor 3.0 Photo	Editor 3.0 Photo
BATE2	45.1	830	0		0	0		Editor 3.0 Photo
BRAZ	72.5	578	4.1	bridge	-8.36	-4.14	Editor 3.0 Photo	Editor 3.0 Photo
CATE1	52.6	447	5.5	bridge	18.33	-7.44	Editor 3.0 Photo	Editor 3.0 Photo
CATE2	93.3	986	5.9		0	-15	Editor 3.0 Photo	Editor 3.0 Photo
CATE3	151.7	1657	9.5		0	-8.38	Editor 3.0 Photo	Editor 3.0 Photo
CREA1	266.9	1496	5.9	wall to wall	-10.36	24.58	Editor 3.0 Photo	Editor 3.0 Photo
CREA2	208.9	2032	0		0	0		Editor 3.0 Photo
CREA3	94.4	1125	7.1	wall to edge	0	-9.45	Editor 3.0 Photo	Editor 3.0 Photo
FAVA1	10.9	77	0		0	0		Editor 3.0 Photo
FORM	164.6	1042	3.25	first bridge on l	-10.07	2.13	Editor 3.0 Photo	Editor 3.0 Photo
FOSC2	138.7	1471	8.6	1st pole at stai	14.33	-5.93	Editor 3.0 Photo	Editor 3.0 Photo
GESU1	128.4	2330	5.2	wall to wall	12.68	0	Editor 3.0 Photo	Editor 3.0 Photo
GESU2	44	456	4.8	left wall to stair	19.95	-6.49	Editor 3.0 Photo	Editor 3.0 Photo
GHET	196.3	1687	10.3	wall to 4th pole	-5.18	12.35	Editor 3.0 Photo	Editor 3.0 Photo
GIOB	274.4	1648	10	pole to pole	6.17	13.47	Editor 3.0 Photo	Editor 3.0 Photo
GOZZ	163.5	1171	10		15.63	-6.93	Editor 3.0 Photo	Editor 3.0 Photo

Figure 21: Table of combined data used in the data catalogue

5.4.4 Data Catalogue

Figure 22 illustrates how the data from each canal segment are presented in the catalogue. It contains the digital image of the portion of the canal segment measured, as well as the MapInfo window of that canal segment in which the measured stretch is marked off by flags. Above the pictures are the information and data we gathered about each canal segment. Appendix I contains the alphabetized reports for every canal segment that we measured; there are two reports per page.



Segmento	Lunghezza (m)	Superficie (mq)	Tratto Misurato (m)	Punti di Riferimento	Velocità Massima Entrante (cm/s)	Velocità Massima Uscente (cm/s)
ACQU2	41	448	6.4	wall to wall	2.41	-0.1

Rio de l'Acqua Dolce

Figure 22: Example of a report

5.4.5 Cartographic Display of Results

The data collected are shown on maps produced with a Geographical Information System called MapInfo. The maps display specific information regarding the name, location, velocity and sediment thickness for each canal segment.

Chapter 6 - Results

This chapter presents the results of our data collection. Data pertaining to individual segments can be found in the reports like the sample in Figure 22 in Appendix I.

6.1 Canal Segments Measured

There are a total of 367 canal segments in Venice, of which we measured the maximum velocities of 133 for incoming and outgoing tides (Figure 23). All but 121 canal segments have been characterized by this and past WPI project teams. A portion of these unmeasured segments includes the 41 segments of the *Canal Grande* and 14 other segments that were not targeted by this study. Since some canal segments were located in the same areas as canals being dredged, and therefore could have altered flows, these segments were considered separately when we analyzed the hydrodynamic behavior of the inner canals of Venice.

Figure 23: Canal segments measured in 1999, before 1999, and not measured

6.1.1 Canals Not Affected By Dredging

Of the 367 canal segments, 110 that were not being affected by dredging were measured during this project. The maximum velocities for both incoming and outgoing tides were obtained for these canals.

6.1.2 Canals Affected by Dredging

Because 6 canal segments were being dredged, 23 canal segments we measured had flows that were possibly affected by dredging (Figure 24).

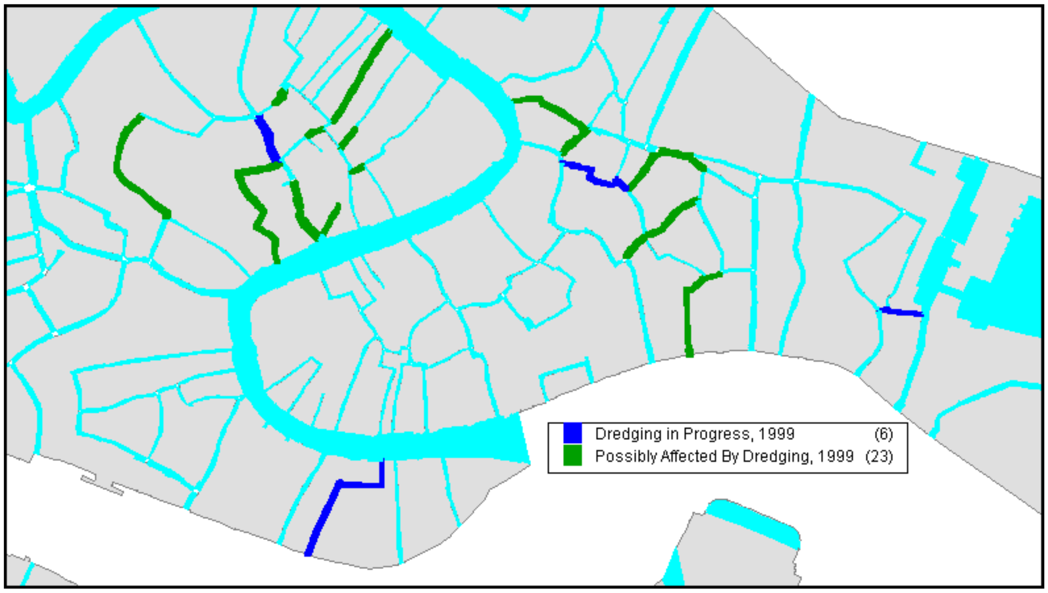


Figure 24: Canals being dredged and those possibly affected by the dredging (Summer 1999)

6.1.3 Distances of the Measured Stretches

Since not every canal segment had an accessible 10 m stretch from which we could take measurements, we were often forced to use different measurement lengths, such as the width of a bridge. Figure 25 is a breakdown of the measurement distances used at each site. This graph shows that the mode, or most recurring value, of the distances measured was 10 m, and that the majority of the distances fell between 8 and 10 meters.

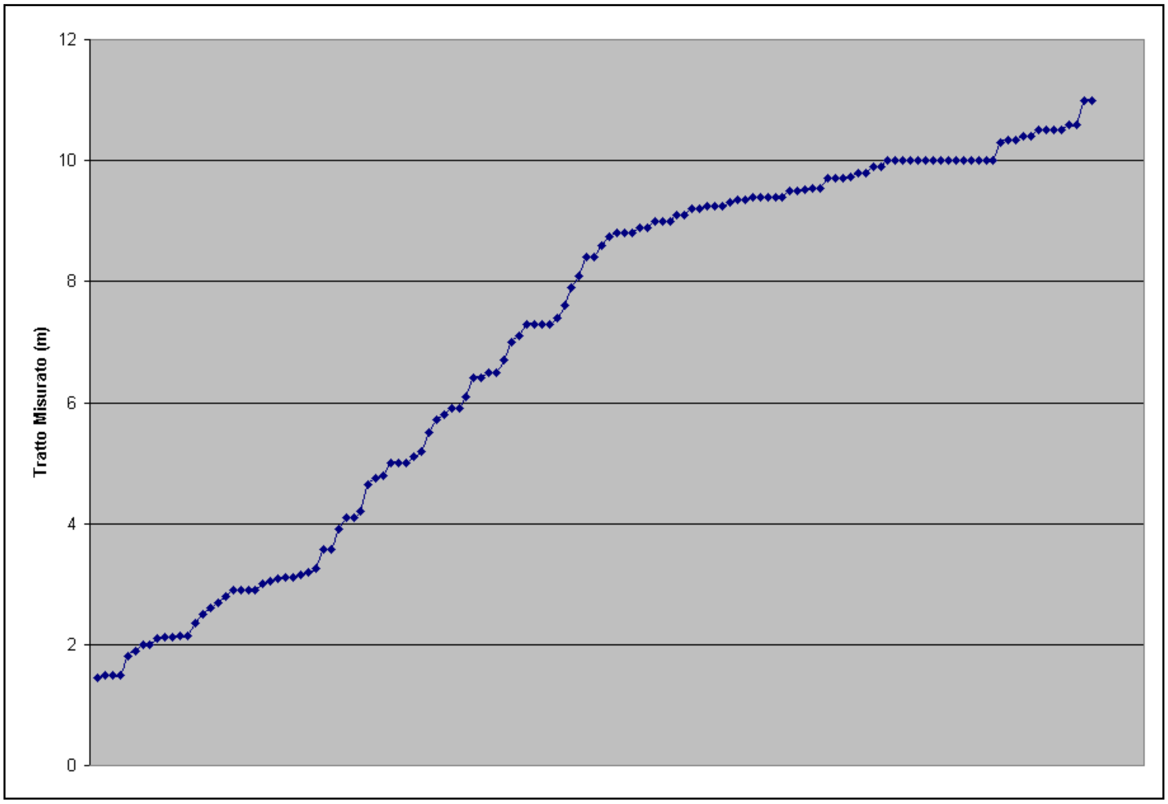


Figure 25: Break down of distances measured

6.2 Canal Segments Not Measured

For various reasons, 66 of the originally targeted canal segments were not measured. In Figure 26, unreachable canal segments are shown in blue, immeasurable canal segments are shown in red, and canals being dredged at the time of our measurements are shown in green.

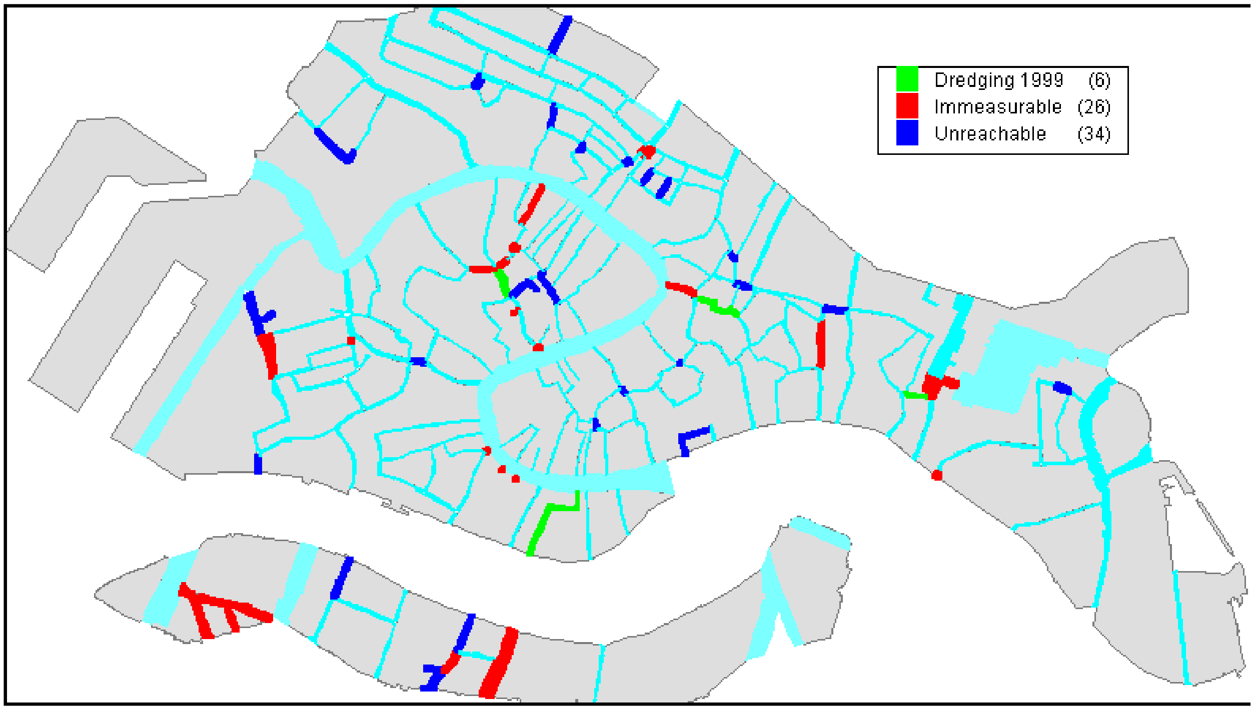


Figure 26: Canal segments that were not measured

6.2.1 Unreachable Canal Segments

The methodology used in this project depends on access to either a bridge or a stretch of embankment along the canal segments to be measured. However, access was not available to all canal segments. This made it impossible for us to gather data for the 34 canal segments colored blue in Figure 26.

6.2.2 Immeasurable Canal Segments

Because of the characteristics of certain canal segments and the limitations of the methods used to gather data, we were unable to measure an additional 27 canal segments that are represented by red in Figure 26. Accurate readings using our flotation device require that it travel in the center of the canal. However, some canal segments were too wide for the device to characterize the flow. Because the flotation device was designed to travel with the current, its path and velocity in the water were affected by wakes caused by boat traffic, resulting in unreliable data. Therefore, we were unable to collect accurate data from canal segments that were heavily trafficked.

6.2.3 Canals Being Dredged

Since the process of dredging requires that the canal be completely sealed off and drained, it was impossible for us to take measurements for the 6 canal segments that were being dredged shown in green in Figure 26. This means that in the future, after those canals have been reopened, it will be possible for those segments to be measured using this project's methodology.

6.3 Hydrodynamic Classification of Canal Segments

The behavior of the water flow for every canal fell into one of four categories that compare the direction of the water flow during incoming and outgoing tides (Figure 27).

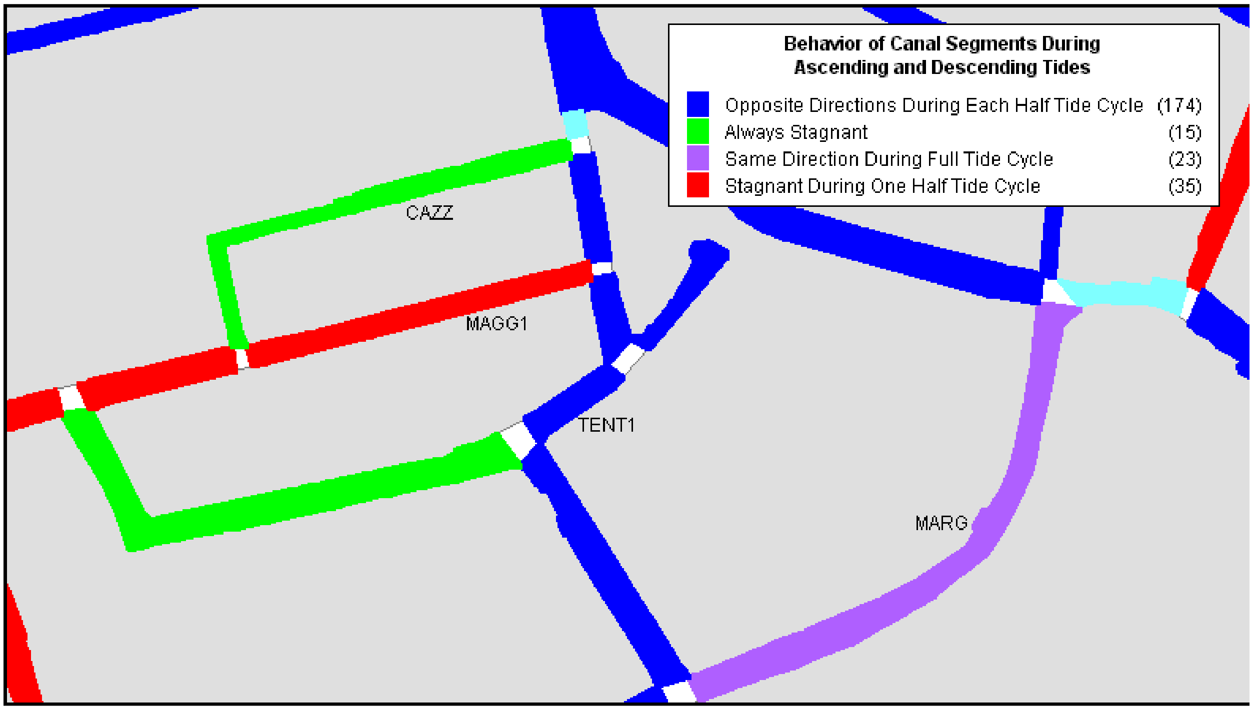


Figure 27: Canal segments representing the four hydrodynamic behavior categories

The 4 categories are as follows:

- Canal segments where the water was stagnant during both incoming and outgoing tides, such as CAZZ shown in green.
- Canal segments where the water was stagnant during one half of a tide cycle and flowed during the other, such as MAGG1 shown in red.
- Canal segments where the water traveled in opposite directions during incoming and outgoing tides, such as TENT1 shown in blue.
- Canal segments where the water traveled in the same direction during both incoming and outgoing tides, such as MARG shown in purple.

6.3.1 Canals Not Affected by Dredging

Of the 110 canal segments measured that were not affected by dredging, the water in 10 segments, (9%), was stagnant during both incoming and outgoing tides, the water in 26 canal segments, (24%), was stagnant during one half of a tide cycle and flowed during the other, the water in 56 segments, (51%), traveled in opposite directions during incoming and outgoing tides, and the water in 18 segments, (16%), traveled in the same direction during both incoming and outgoing tides (Figure 28). Appendix J contains all data for canals not affected by dredging.

6.3.2 Canals Affected by Dredging

The flow in the 23 canal segments close to canals being dredged resulted in a different pattern of water flow behavior. The water in one canal segment (4%) was stagnant during both incoming and outgoing tides, the water in 5 segments, (22%) was stagnant during one half of a tide cycle and not the other, the water in 16 segments, (70%) flowed in opposite directions during incoming and outgoing tides, and the water in 1 canal segment (4%) flowed in the same direction during both incoming and outgoing tides (Figure 29).

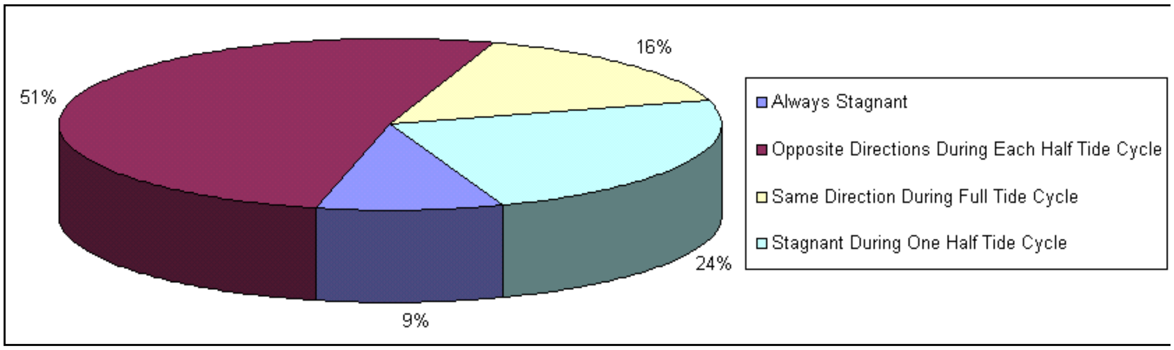


Figure 28: Categorization of hydrodynamic behavior in canals not affected by dredging

6.4 Observed Maximum Velocities

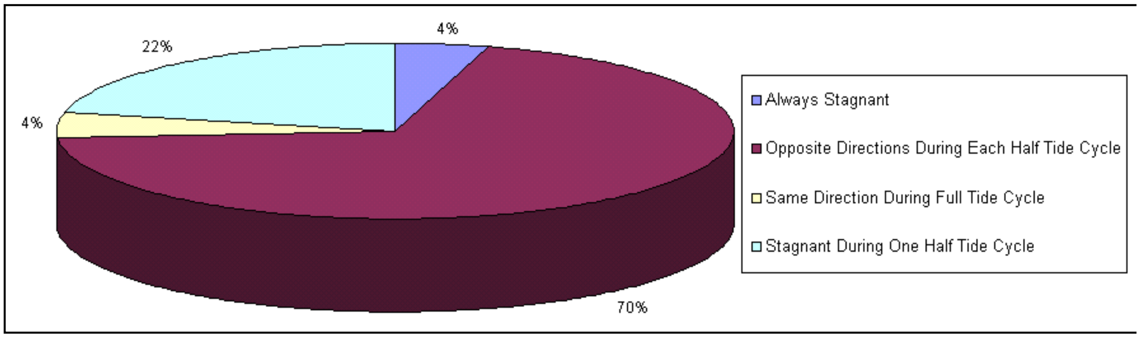


Figure 29: Categorization of water flow behavior in canals affected by dredging

The water speeds in the canals were divided into 4 ranges. The stagnant canals, or *rii stagnanti*, had maximum flow speeds less than or equal to 1 cm/s. Canals with a maximum flow speed greater than 1 and less than or equal to 10 cm/s were considered to be lazy, or p*igri*. The canals with mid-range maximum speed, or *rii mediamente vivaci*, traveled at a speed greater than 10 and less than or equal to 20 cm/s. In fast canals, *rii vivaci o veloci*, the water traveled at a maximum speed greater than 20 cm/s.

6.4.1 Current Velocities of Incoming Tides

During the incoming tide, 33 or 15% of the segments were stagnant, the currents in 16 segments, or 7% were slow, 117 or 52% were medium, and 57 segments, or 26%, were fast (Figure 30).

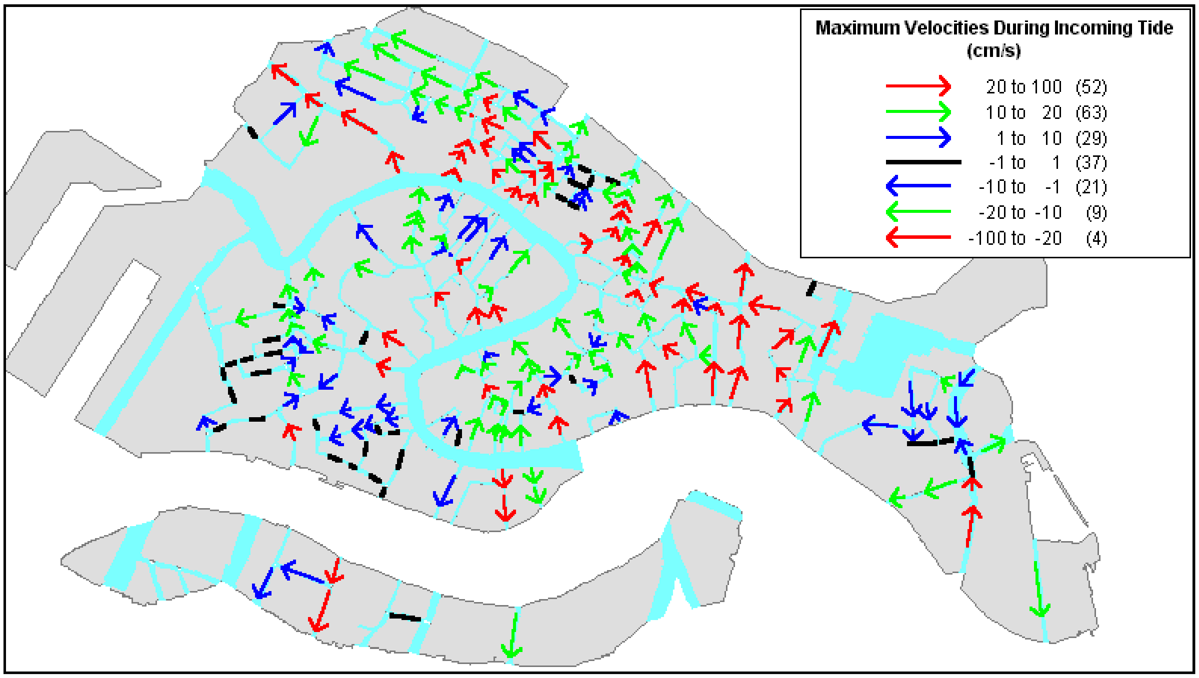


Figure 30: Maximum velocities during incoming tides

6.4.2 Current Velocities of Outgoing Tides

During descending tides, 20**,** or 9% of the canal segments were stagnant, 19, or 8% had slow speeds, 127, or 58% had medium flows, and 57, or 25% were fast moving (Figure 31).

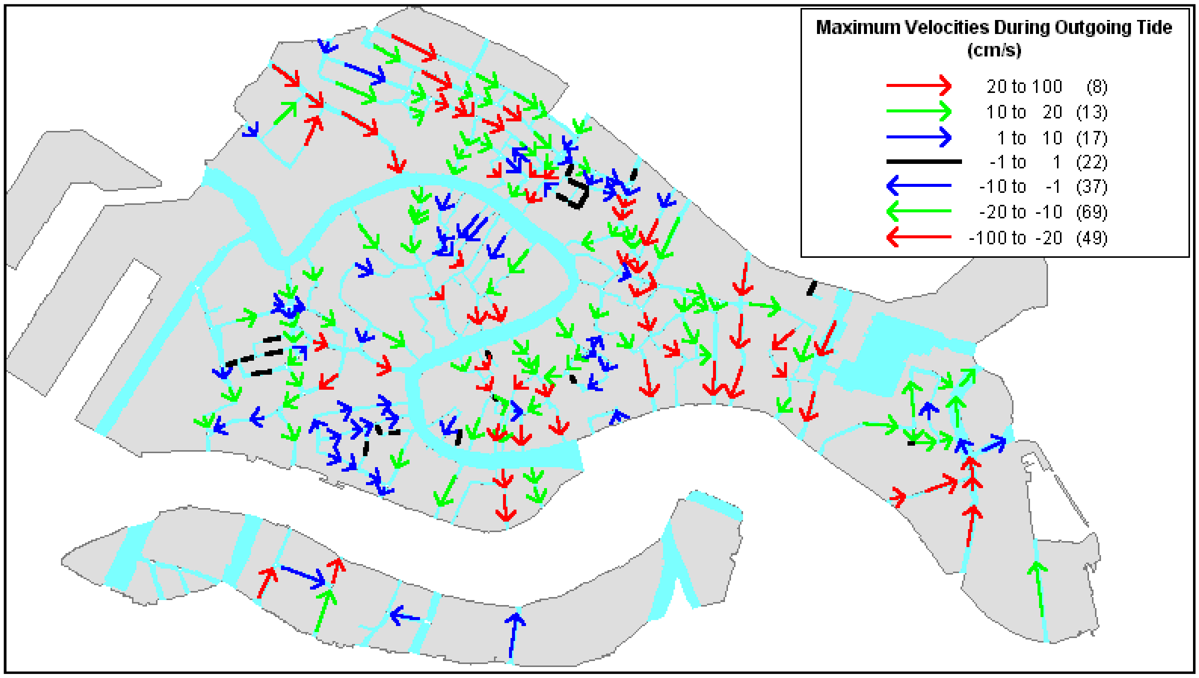


Figure 31: Maximum velocities during outgoing tides

Chapter 7 - Analysis

In this section we analyze the combined results of our study and past WPI studies. This section explains anomalous hydrodynamic behavior of canals and establishes correlations between our velocity data (Appendix K) and sedimentation data obtained from past studies (Appendix L).

7.1 Anomalous Directional Hydrodynamic Behavior in Canal Segments

In most cases, the water flowing through the canals follows certain patterns, making it possible to predict what direction the water will be traveling through particular canal segments during incoming and outgoing tides. However, there are several cases in which the flow behavior deviates from the expected patterns.

The water flowing through the canals is expected to travel in a northern direction during ascending tides. This is because tidal water from the Lagoon enters the city from the southeast and flows northwest. As the tidal water exits Venice, it flows in a southerly direction towards the Lagoon. However, not all canals follow these expected patterns. This section hypothesizes why these discrepancies occur.

7.1.1 Canals Flowing in the Same Direction During Incoming and Outgoing Tides

In contrast to predicted behavior of the canals, the flow of some canals did not change direction despite a reversal of the overall tidal flow through the Lagoon (Figure 32). Constant direction of flow was observed in 17 canal segments. This behavior can be explained for the eastern section of *Dorsoduro* in the canals *Rio di S. Vio* (VIO), *Rio della Fornace* (FORN1 and FORN2), and *Rio della Salute* (SALU1 and SALU2). These segments flow in a southern direction during both tides, which is not the expected behavior. Presumably, this is due to the fact that when the tide comes in, a large amount of water enters both the *Giudecca Canal* and the *Canal Grande.* Since the *Canal Grande* is much narrower and more curved than the *Giudecca Canal,* the water flows more swiftly through the *Giudecca Canal*. The curves of the *Canal Grande* cause the water to slow down and its level to rise, so that it is higher than in the *Giudecca Canal*. Therefore, the water flows down from the higher level to the lower level through the previously mentioned canal segments. As the tide goes out, the water level in the *Canal Grande* is once again higher than the water level in the *Giudecca Canal* because the latter empties more rapidly. Therefore, the water travels south through eastern *Dorsoduro.*

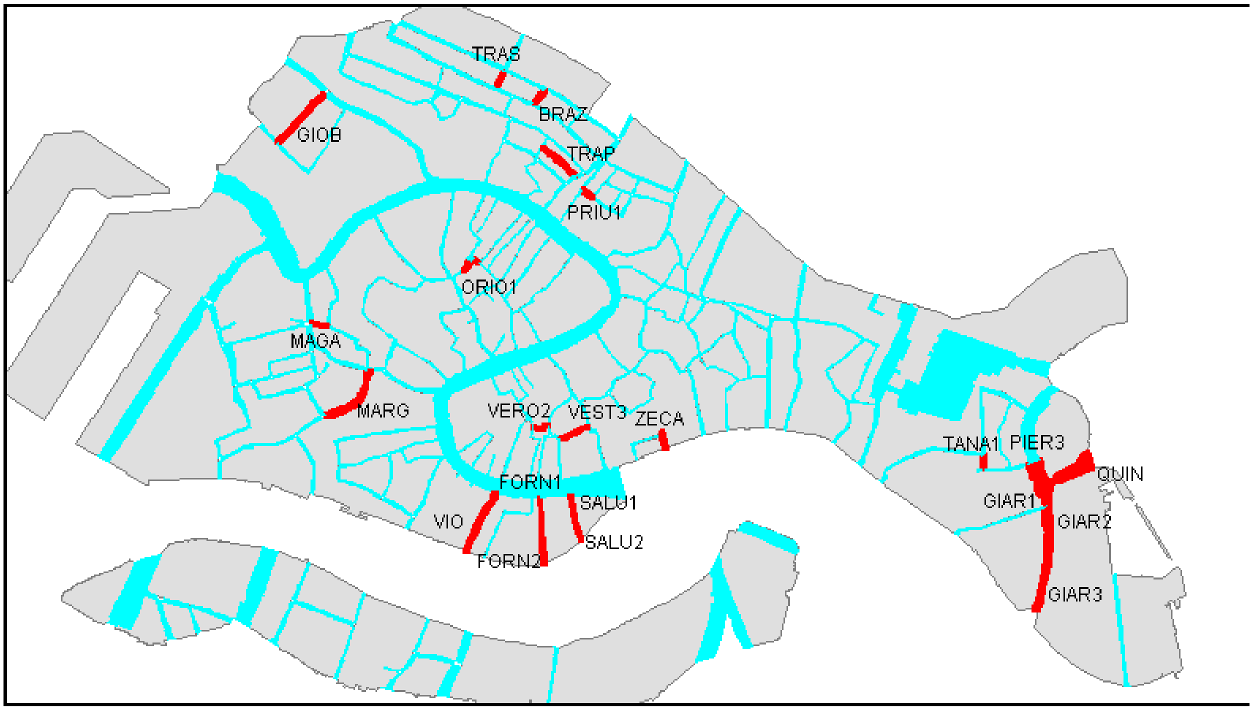


Figure 32: Canal segments that flowed in the same direction during incoming and outgoing tides

7.1.2 Canals Flowing in Unexpected Directions During Incoming Tide

Some canals flowed in a direction opposite to that expected during the incoming tides (Figure 33). This behavior was observed especially in eastern *Castello* and in the *Giudecca.*

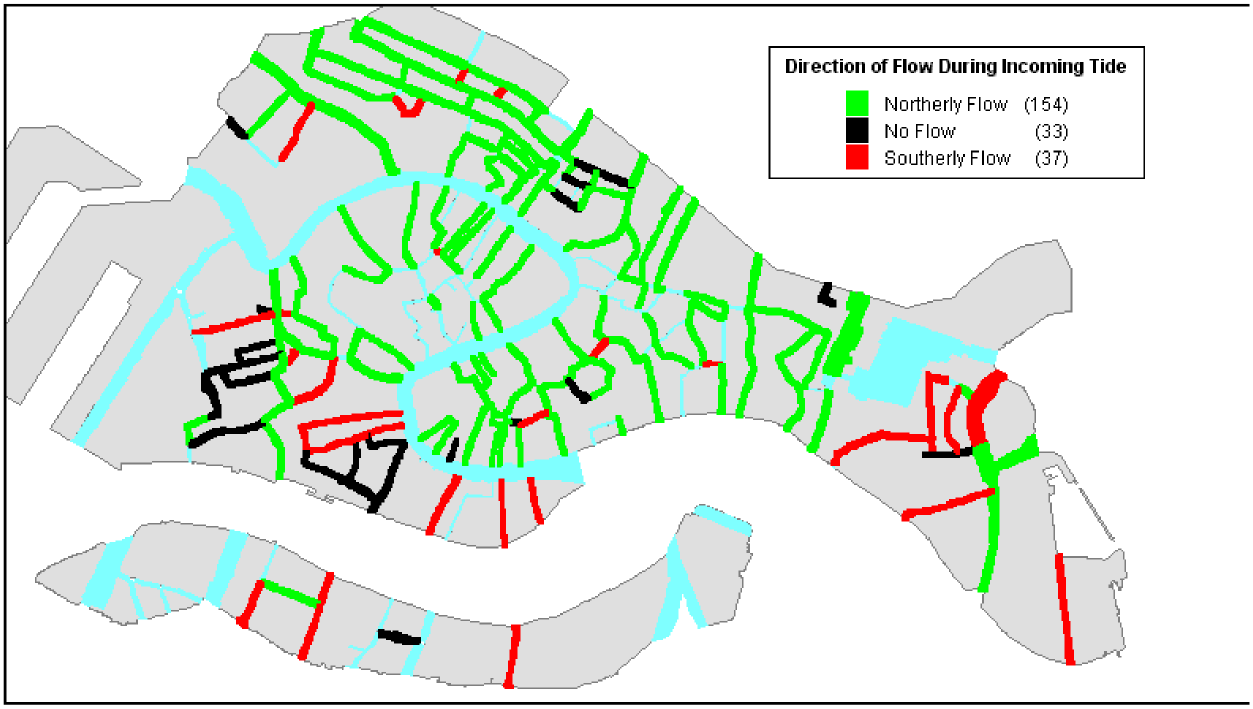


Figure 33: Map showing direction of flow during incoming tides

The peninsula near the *Arsenale* affects the water flow through the canals in the eastern Castello region. This landmass allows for the accumulation of water near the *Arsenale's* entrance to the Lagoon, causing its level to be higher than that of the canals to the south. Therefore, because water flows toward lower levels, it empties into *Canale di San Pietro* and adjacent canals, thus causing them to have a southerly flow even though the tide is moving north (Figure 34).

A second area that exhibits unexpected flow direction during incoming tides is the *Giudecca.* All of the canals that connect the *Giudecca Canal* and the Lagoon flow south. This is because the water level in the *Giudecca Canal* becomes slightly higher than that of the Lagoon as the tides enter, thus causing the water to flow south into the Lagoon.

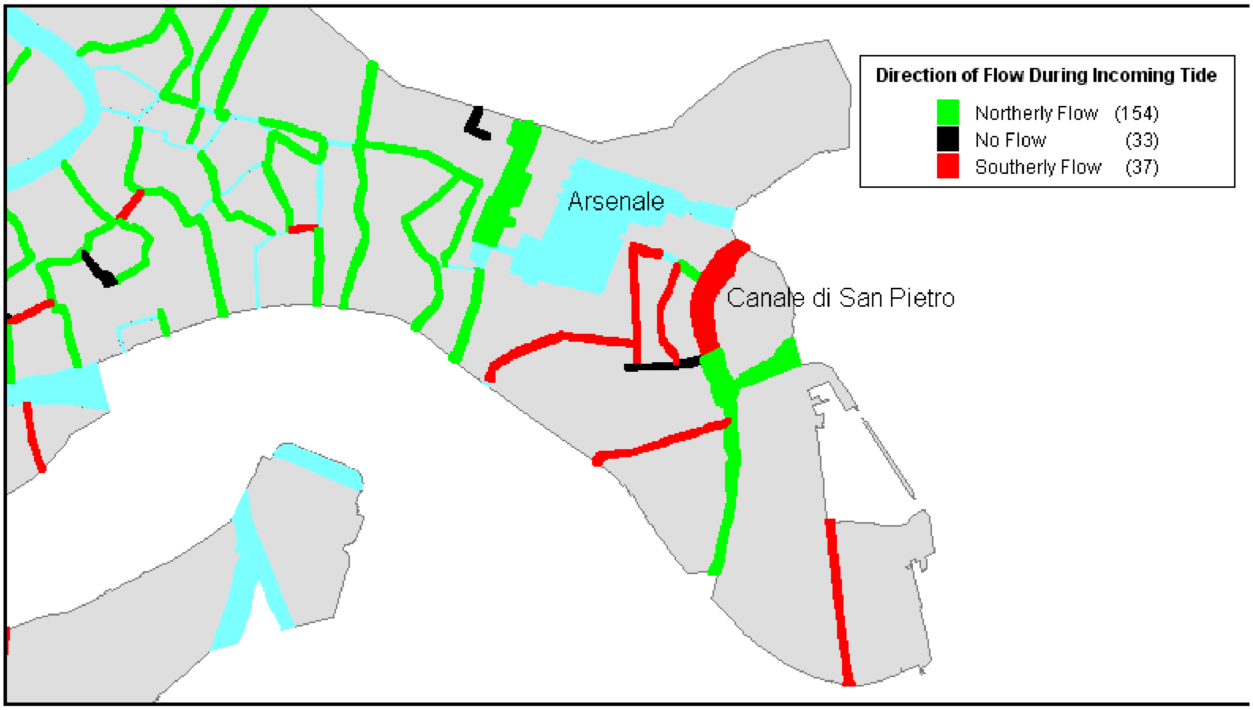


Figure 34: Direction of flow in eastern *Castello* during incoming tide

7.1.2.1 Canals Flowing in Unexpected Directions During Outgoing Tide

Again, the canals in the *Castello* region flow in an opposite direction to that expected (Figure 35). As the tide goes out, these canals flow north. This is most likely because of the peninsula near the A*rsenale* that provides a barrier between these canals and the northern part of the Lagoon. This barrier prevents water from flowing into the area directly south of it during outgoing tides. At the same time, the water level of the *Bacino di San Marco* becomes higher due to the water deposited into it from the *Canal Grande* and the *Giudecca Canal*. This difference in water level causes the water in the *Bacino di San Marco* to travel north through the canals.

Figure 35: Map showing direction of flow during outgoing tides

The *Giudecca* canals also flow in an unexpected direction during descending tides. It is possible that as the water in the *Giudecca Canal* flows into the Lagoon, it pulls the water from the canals in the *Giudecca* with it, so that the water flows in a northerly direction.

7.2 Variation and Distribution of Current Velocities

To characterize and find patterns in the data collected, average maximum speeds of the water flow were compared. Histograms were employed to show the distribution of the speed measurements.

7.2.1 Average Current Speeds in all Segments Measured

Not all of the canals flowed at the same maximum speed for both ascending and descending tides. Both incoming and outgoing tides produced nearly equivalent average speeds, with that for the descending tide being slightly faster. The average flow speed was 13.8 cm/s for ascending tides and 14.7 cm/s for descending tides. A reason for this difference is that 33 canal segments had no flow during ascending tides, but only 20 canal segments had no flow during descending tides.

The canal segments that showed the most interesting differences in speed were those that flowed during one half of the tide cycle and were stagnant during the other (Figure 36). These segments do not exhibit expected behavior and make the need for validation of the flow model apparent, since it would be difficult to intuitively predict the hydrodynamic behavior in these segments. For a list of the percentage differences in each canal speed between ascending and descending tides see Appendix M.

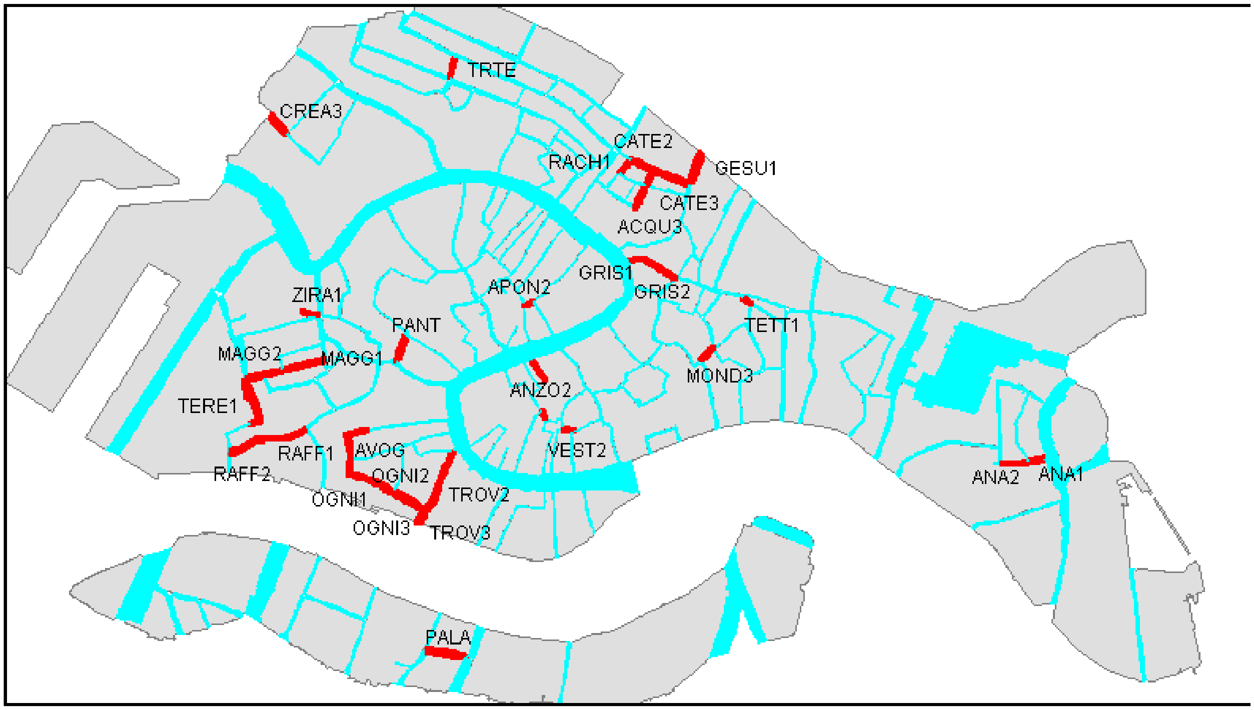


Figure 36: Segments that only flowed during one half of the tide cycle

7.2.2 Distribution of Canal Flow Speeds

Histograms were created to show the distribution of the flow measurements for ascending and descending tides (Figure 37 and Figure 38).

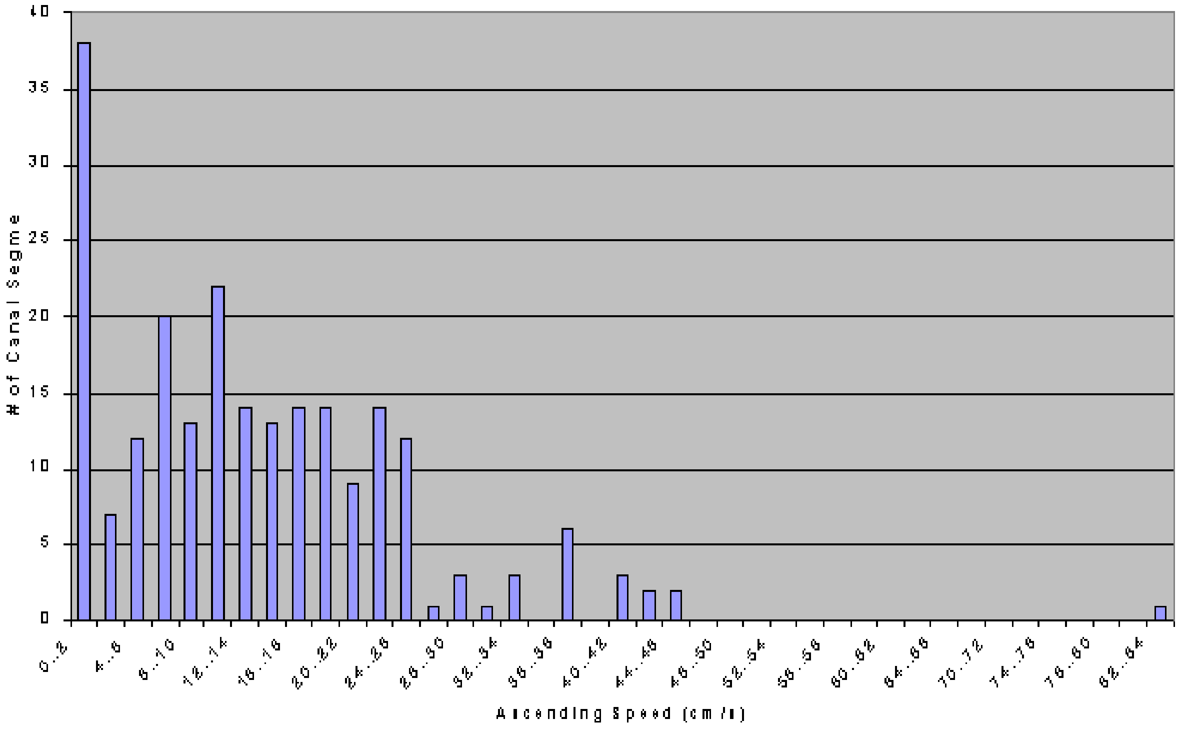


Figure 37: Distribution of maximum current speeds during incoming tides

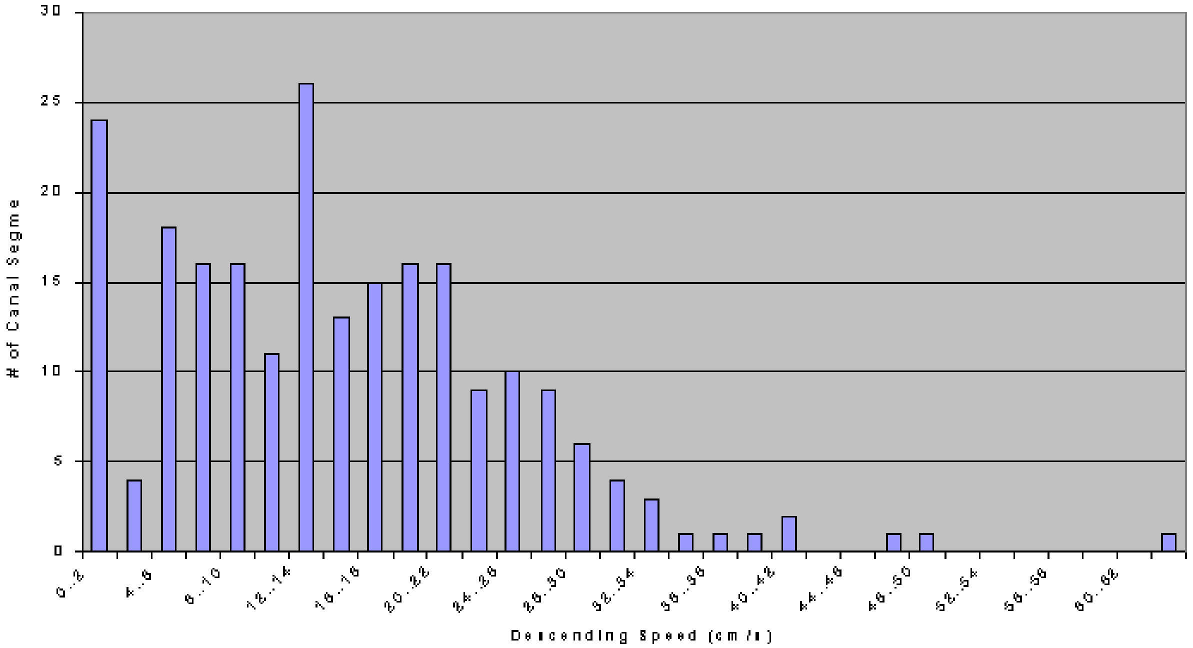


Figure 38: Distribution of maximum current speeds during outgoing tides

The box plot (Figure 39) shows that the first and third quartiles during ascending tides are 5.9 and 20.0 cm/s, respectively. For descending tides, they were 7.4 and 20.4 cm/s, respectively. This means that the middle 50% of the velocities (Inter-quartile Range or IQR) fall between those numbers. By multiplying 1.5 by the IQR (the range between Q1 and Q3), the outliers, or extreme values, were able to be determined. These values are limited to the fastest canals because the speeds are cut off at 0 cm/s.

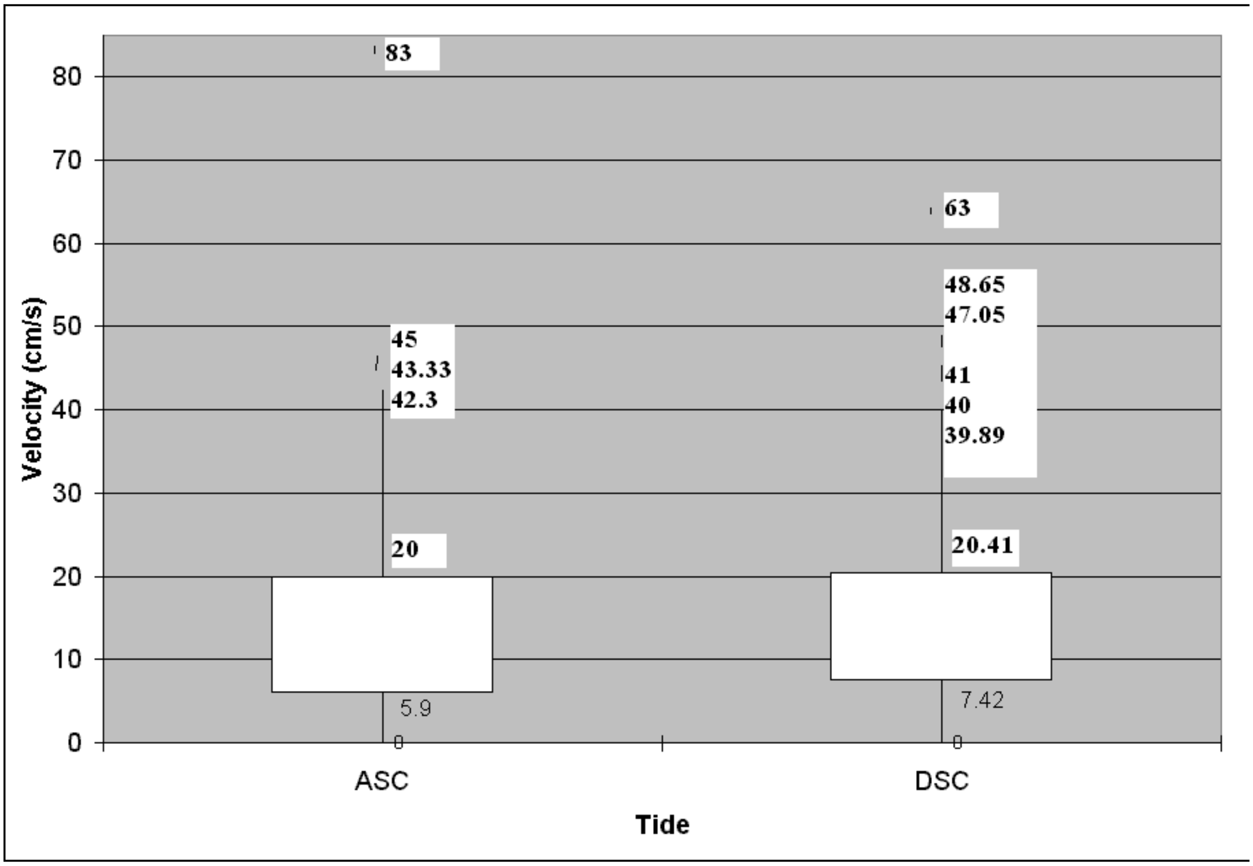


Figure 39: Boxplot showing the speed distribution during incoming and outgoing tides

The canal segments through which the water flowed the fastest during ascending tides are NOAL3 (43.33 cm/s), APOS3 and APOS4 (45 cm/s), and GALE1 (83 cm/s). For descending tides the fastest speeds were GIUS (40 cm/s), ARSE (41 cm/s), CANN3 (47.06 cm/s), CANN4 (48.66 cm/s), and GALE1 (63 cm/s) (Figure 40).

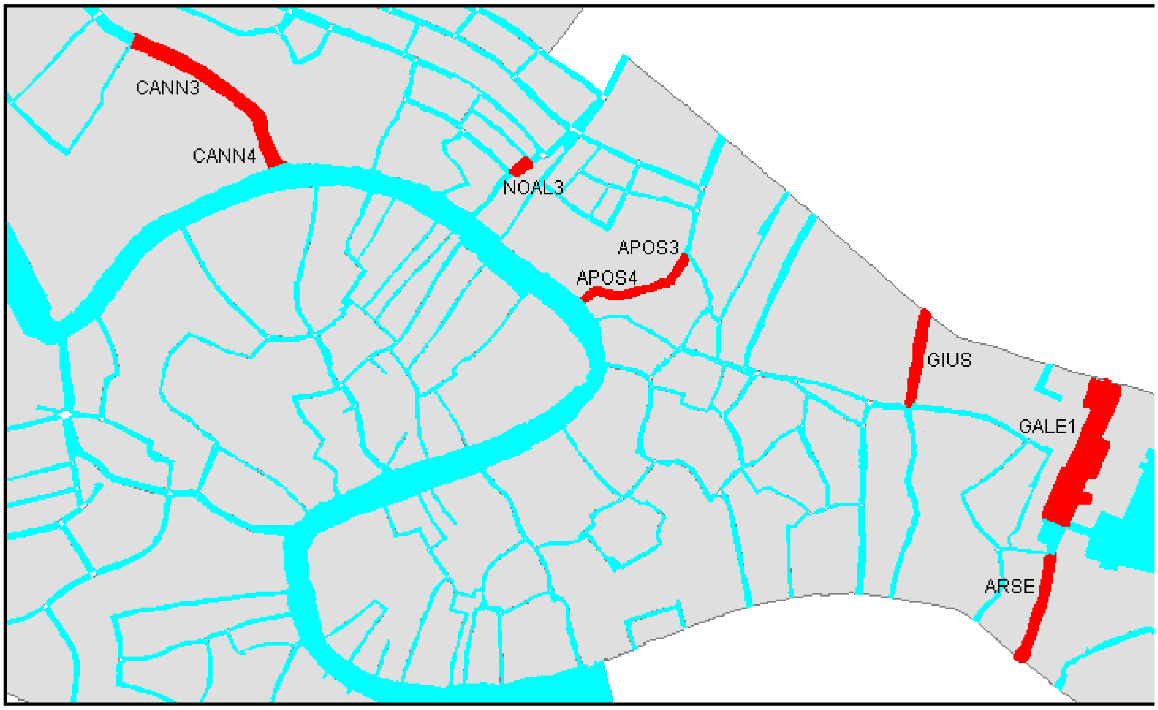


Figure 40: Map showing the location of the canals with unusually fast currents

7.3 Flow Speeds With Respect To Distance from the Canal Grande

It is possible to determine a relationship between the velocity of the water in a particular segment and its distance from the *Canal Grande.*

7.3.1 Incoming Tides

During ascending tides, the *Canal Grande* fills with water flowing in from the Lagoon. This causes the water level in this canal to be higher than in the surrounding canals. In order to return to equilibrium, the *Canal Grande* distributes its water into the secondary canals. In Figure 30, it is apparent that the canal segments with the fastest velocities are those that receive water directly from the *Canal Grande*. As the water flows farther from the segments connected to the *Canal Grande,* the gradient of the water level decreases, causing the speed of the water to decrease. A specific example illustrating this phenomenon occurs in the area southwest of the *Canal Grande*. The canal segments receiving the water from the southern end of the *Canal Grande* have the highest flow rates. As the water travels further into the inner canals, the speed decreases, eventually becoming stagnant in the canal segments furthest from the *Canal Grande*.

7.3.2 Outgoing Tides

There is not as clear a pattern for the relationship between proximity to the *Canal Grande* and the velocities in the canal segments for descending tides as there is for ascending tides (Figure 31). It appears that during descending tides the water speeds are randomly distributed through the city. This could possibly be due to the fact there are more entrances for water to flow in on the northwestern side of Venice than on the southeast, thus spreading out the buildup of incoming water more evenly. However, one regularity is still noteworthy. All of the stagnant canal segments (except for one) are either tertiary segments that are located far from the *Canal Grande* or are segments that are only connected to one canal.

7.4 Relationships Between Sediment Accumulation and Hydrodynamic Behavior in Canal Segments

We combined our velocity data with sediment depth data that were collected by previous WPI projects for 99 canal segments (Figure 41). This combination of data enabled us to determine if any correlation exists between the velocity of water and sediment accumulation.

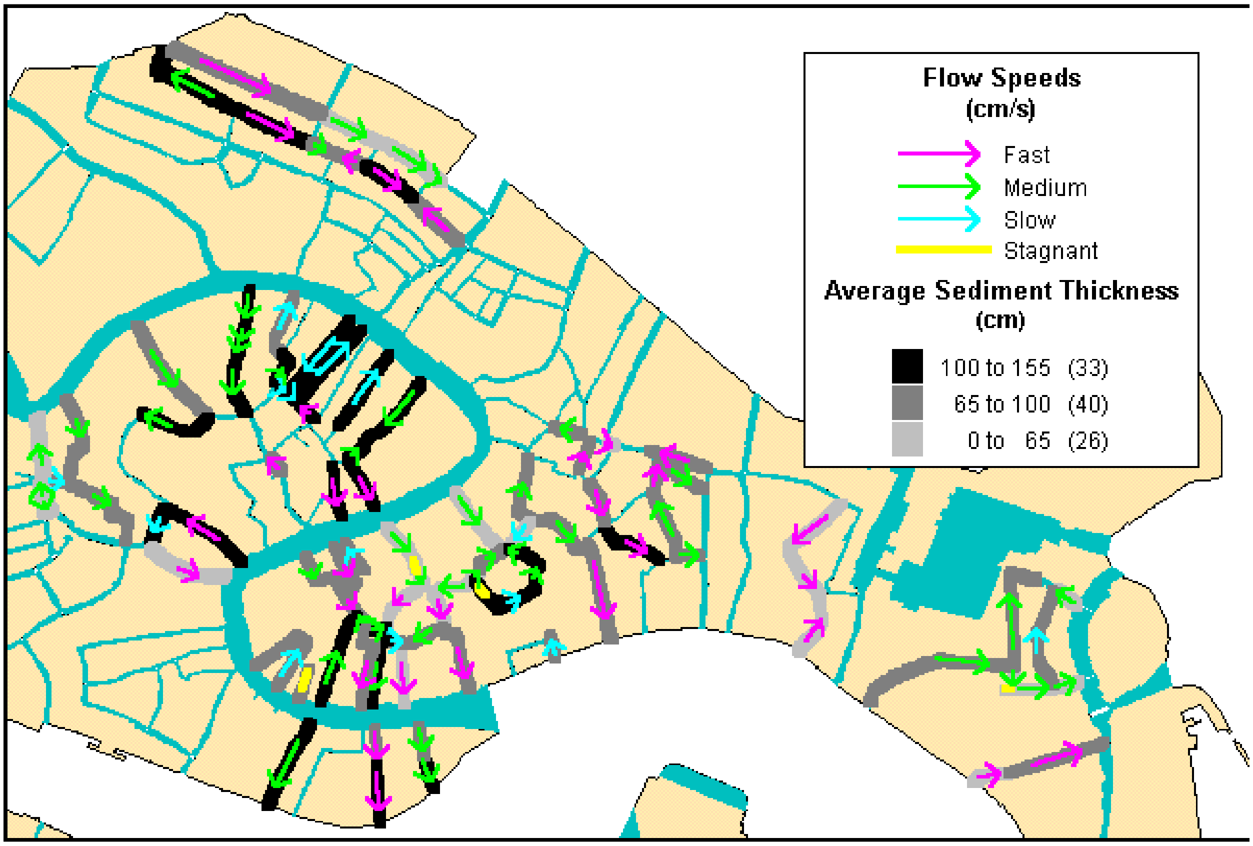


Figure 41: Velocity vs. sediment thickness

7.4.1 Current Velocity vs. Sediment Accumulation

From simply observing the map, it is difficult to find any correlation between sediment thickness and velocity. Instead, we observed that greater sediment accumulation occurred in certain areas, such as northwestern *Cannaregio* and *San Polo*, regardless of the velocity of the water. However, once the velocity was plotted against the sediment depth, a very loose correlation was found. This graph (Figure 42) shows that as the velocity increases (blue line) the sediment depth decreases (dotted red line). Since both lines have almost the same slope this correlation is not very strong.

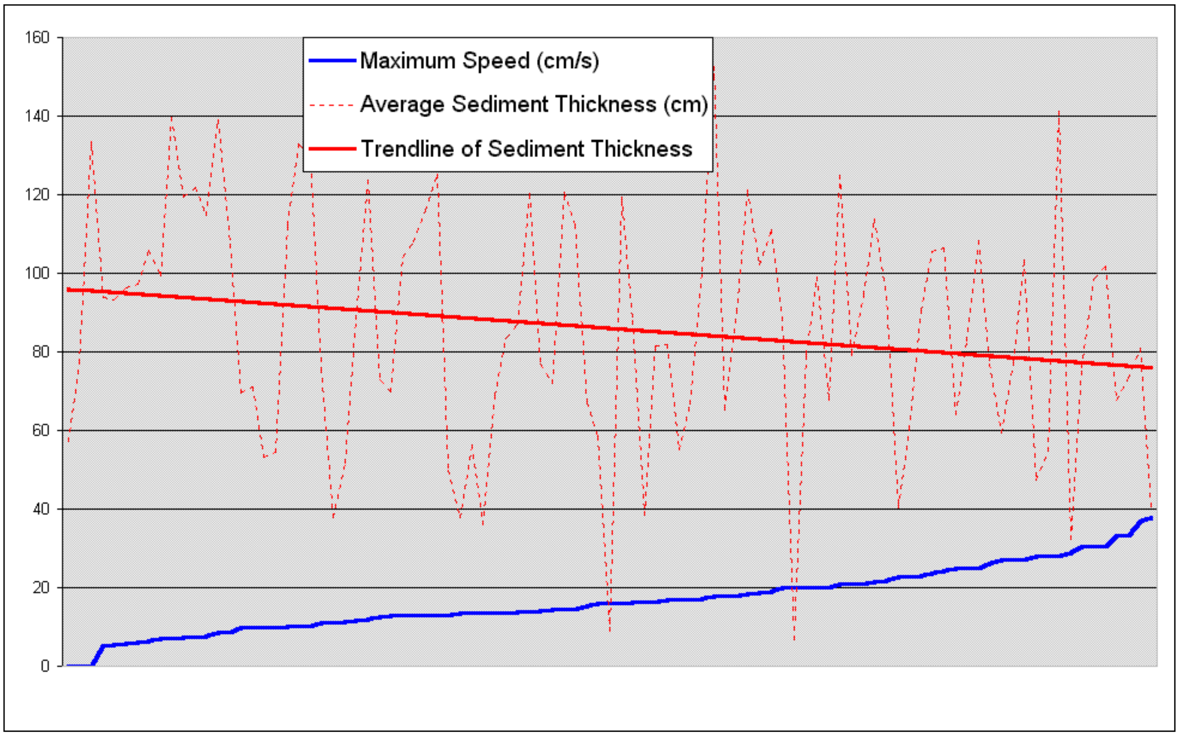


Figure 42: Graph of velocities related to sediment depth

7.4.2 Flushing Ability vs. Sediment Accumulation

Next, the relationship between the velocity of the water flow and the distance the water must travel through the canal was considered. This was to account for the fact that even though a particular segment may flow at a high velocity, the water carrying the sediment may still not have enough time to exit the canal if the segment is sufficiently long before the reverse tide begins. To quantitatively describe this relationship, we computed an index to represent the flushing capacity of a segment as a function of its hydrodynamic characteristics and its length (Appendix N). The flushing index is the ratio of the total distance traveled by water flowing at the maximum speed in a given segment over a 6 hour period to the length of the canal segment (Figure 43). This is known in Italian as '*ricambioidrico*'. From these calculations, we observed a relationship between the canal segment length and the likelihood of the water having enough time to flush the sediment out of the canal. The legend in Figure 43 shows the numeric flushing

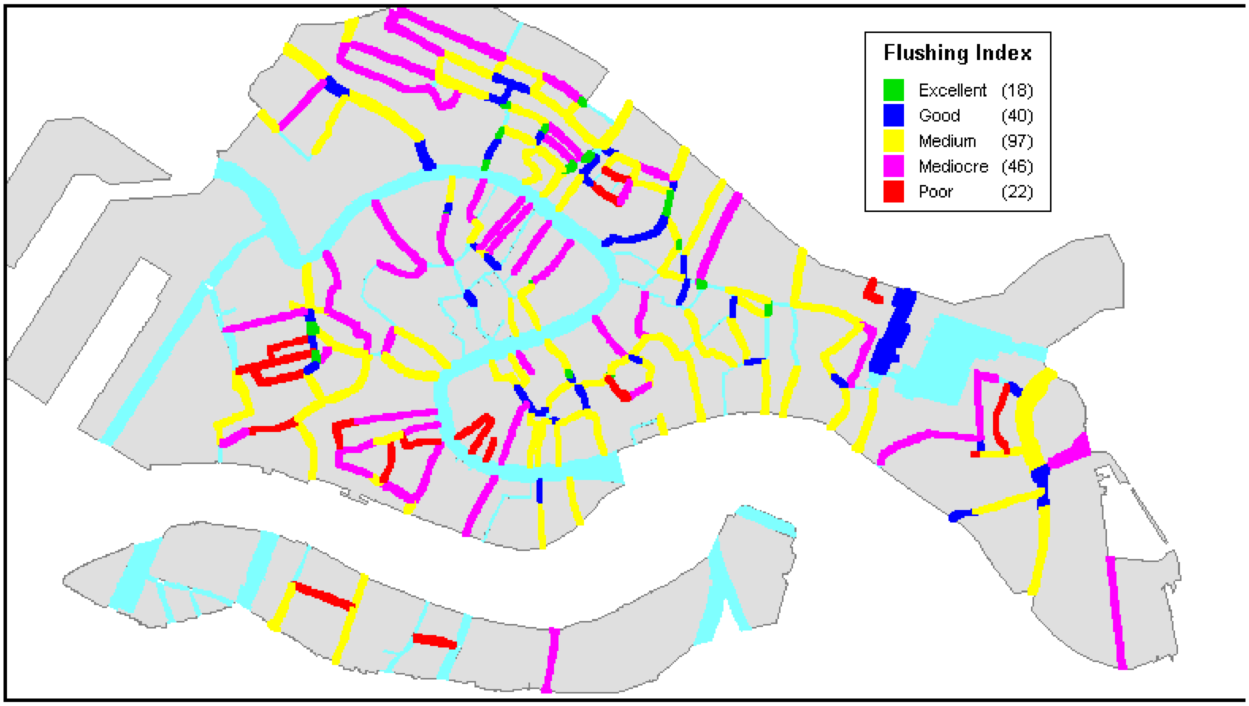


Figure 43: Map indicating flushing indices

indices as qualitative flushing capacities. As expected, in most instances short segments have higher flushing indices while long segments have smaller ones.

We compared the flushing capacity of the water to the amount of sediment in each of the canal segments for which there were data. In Figure 44, it is apparent that the higher the flushing index of a canal segment, the less sediment accumulation occurs. In *Cannaregio* for instance, the canal segments had low flushing indices and therefore high accumulation of sediment despite the fact that the canal segments had relatively high velocities. This example illustrates why a high velocity does not always yield low sediment buildup.

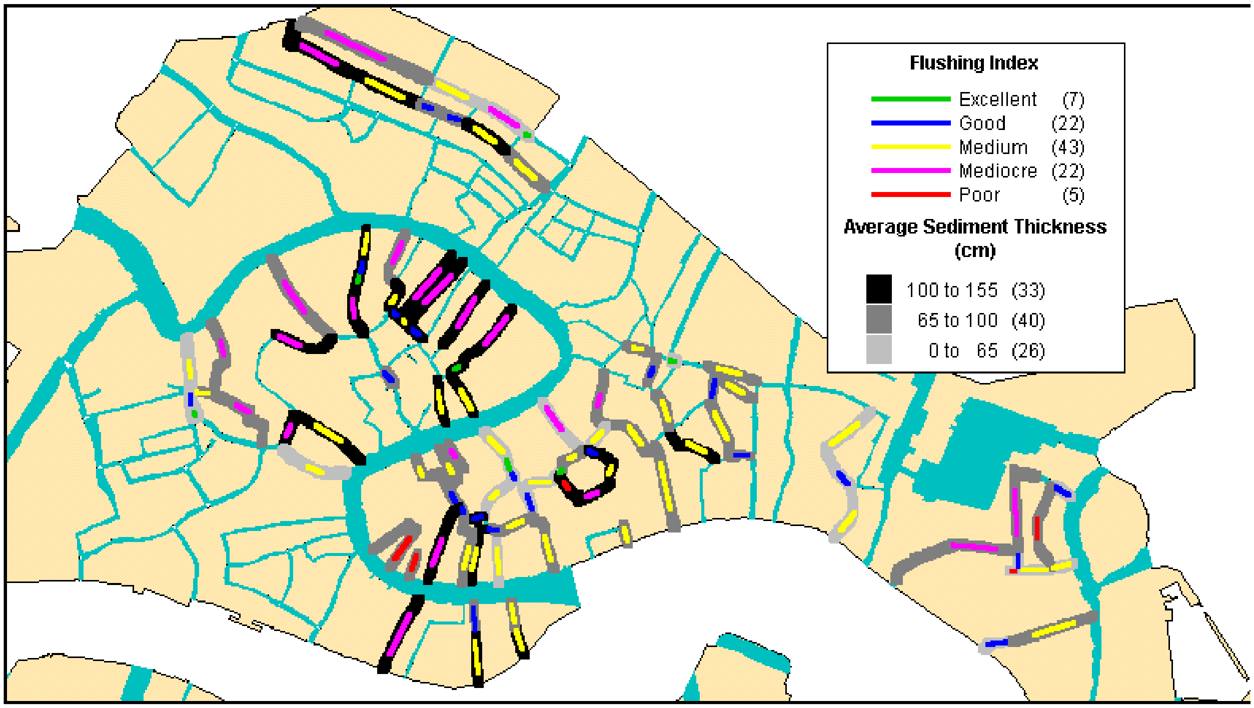


Figure 44: Sediment thickness compared to flushing indices

Figure 45 represents the general relationship between flushing indices and sediment levels. This graph shows that there is a much stronger correlation between the flushing index and sediment thickness than between velocity and sediment depth. This is apparent because the trendline of the sediment thickness, shown in red, has the same slope as in Figure 42. By comparing the blue lines of the two graphs it is apparent that the flushing index has a much steeper slope than the velocity line. This steeper slope, as compared to the trendline of the sediment thickness, shows a strong correlation, whereas the gradual slope in Figure 42 indicates a loose correlation.

The Flushing Index describes a particular canal's ability to remove sediment in relation to other canals. However, it alone is not capable of describing the total sediment accumulation of a canal. Sediment input from other canals, and flow behavior such as water flowing in the same direction during an entire tide cycle, also play important roles in the sediment accumulation of a segment. This index provides useful information because canals that have a high index number would still have the ability to remove sediment even if it came from outside sources, such as other canals. Canals that have a lower index number would still be accumulating the most sediment, regardless of where it comes from. However, we did not have enough data regarding these factors to make definite conclusions as to how they affect sediment accumulation. This cannot be done without a more complete characterization of the flow velocities of each segment for the duration of an entire tide cycle, rather than just at the point of their maximum velocities. Studies regarding the amount of sediment entering canals from adjacent canals would also be necessary to derive those conclusions.

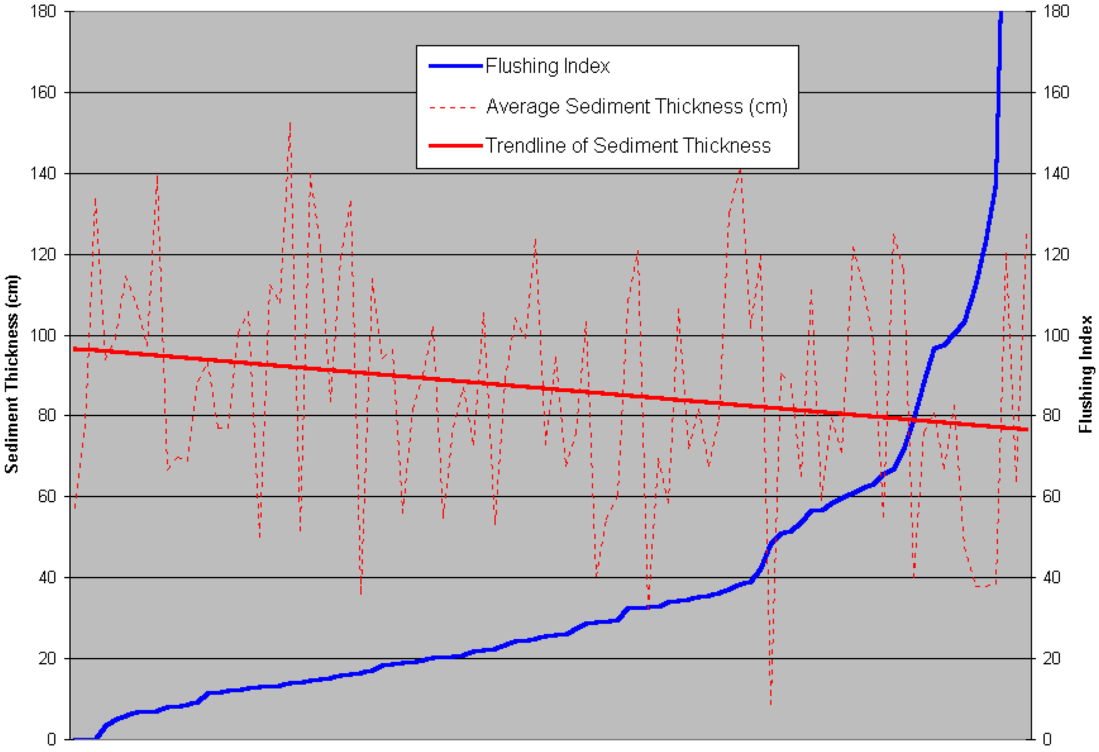


Figure 45: Flushing indices related to sediment thickness

7.5 Canals Affected by Dredging

Our velocity results collected during incoming (Figure 46) and outgoing (Figure 47) tides for canal segments adjacent to canals being dredged are the first measurements ever obtained for canals affected by dredging (Appendix O). Since there are no data regarding water velocity for these segments before the dredging began, we are not able to determine if the water flow has changed substantially because of the dredging. However, since the canal system in Venice is a network in which all canal flows affect one another, it is reasonable to assume that the canals close to a blocked canal are not behaving as they normally would.

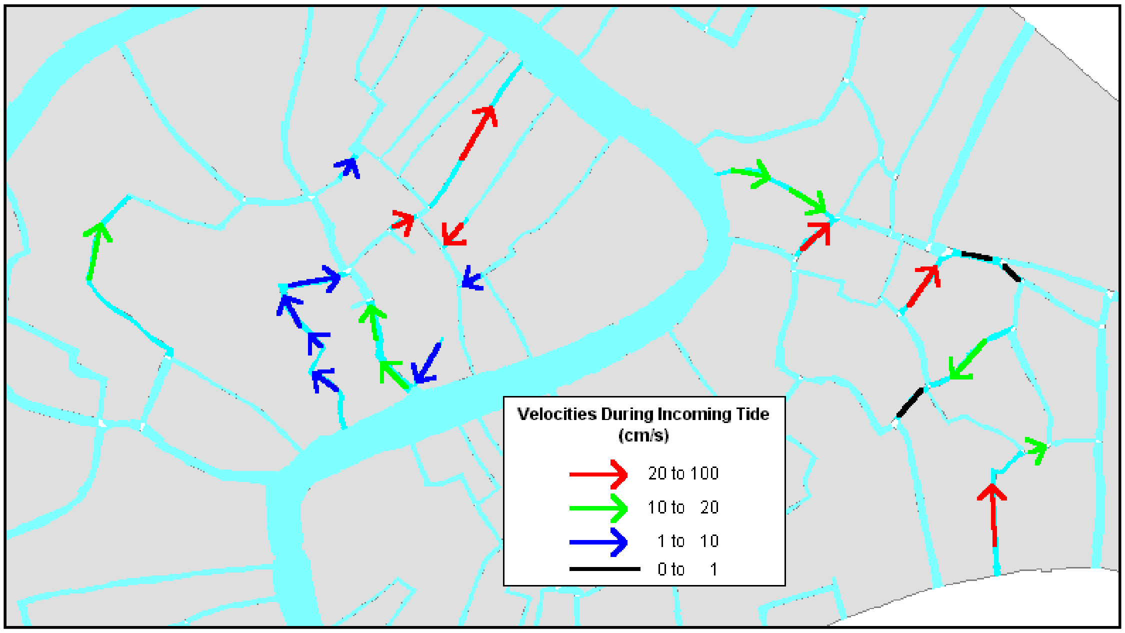


Figure 46: Velocity of canals affected by dredging during incoming tides

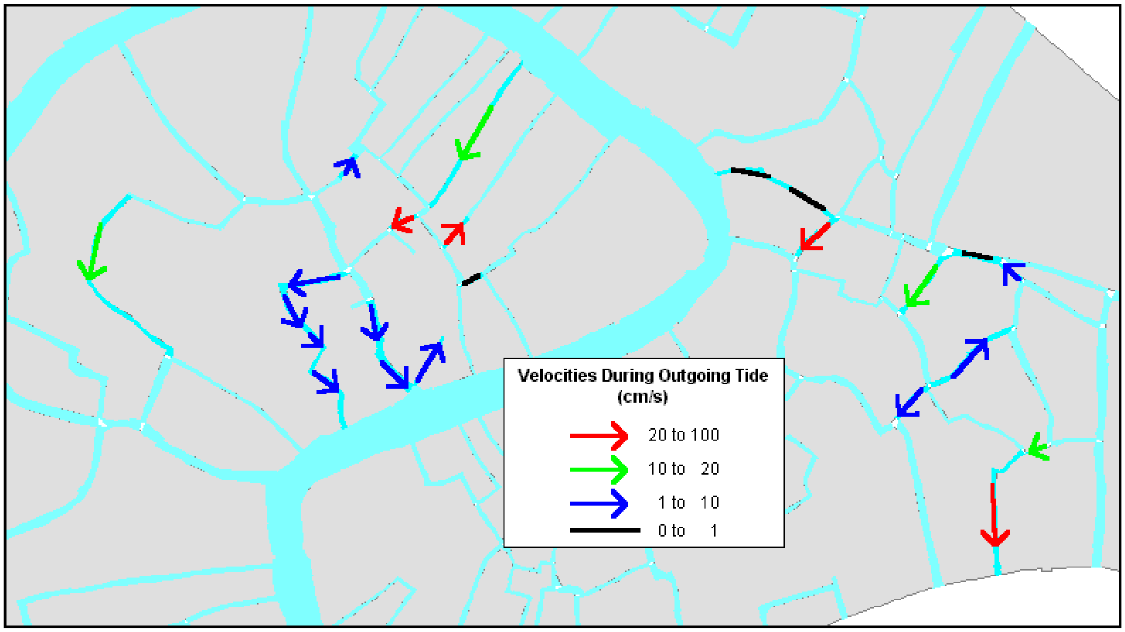


Figure 47: Velocity of canals affected by dredging during outgoing tides

7.6 Flow Model Verification

The validation of the flow model is an important example of the use of the data obtained in this project. Despite the fact that this model accurately describes the flow characteristics of many of the canal segments, it is still not capable of accurately predicting the flows through the entire network of canals. An example of an error between the model and our data occurs in eastern Dorsoduro. According to the model (Figure 48 and Figure 49), *Rio de la Fornasa* has almost no flow during either incoming or outgoing tides, *Rio de la Salute* flows southward very quickly during incoming tide and northward at a medium speed during outgoing tide, and *Rio de San Vio* flows slowly northward during incoming tide and slowly southward during outgoing tide. Our data however shows that all three canals flow southward during both incoming and outgoing tides. *Rio de la Fornasa* flows slowly during incoming and at a medium speed during outgoing, *Rio de la Salute* flows at a medium speed during both tides, and *Rio de San Vio* flows quickly during both. This discrepancy makes the need for the validation of the flow model more apparent, therefore collecting field data such as ours is essential to the completion of an accurate model.

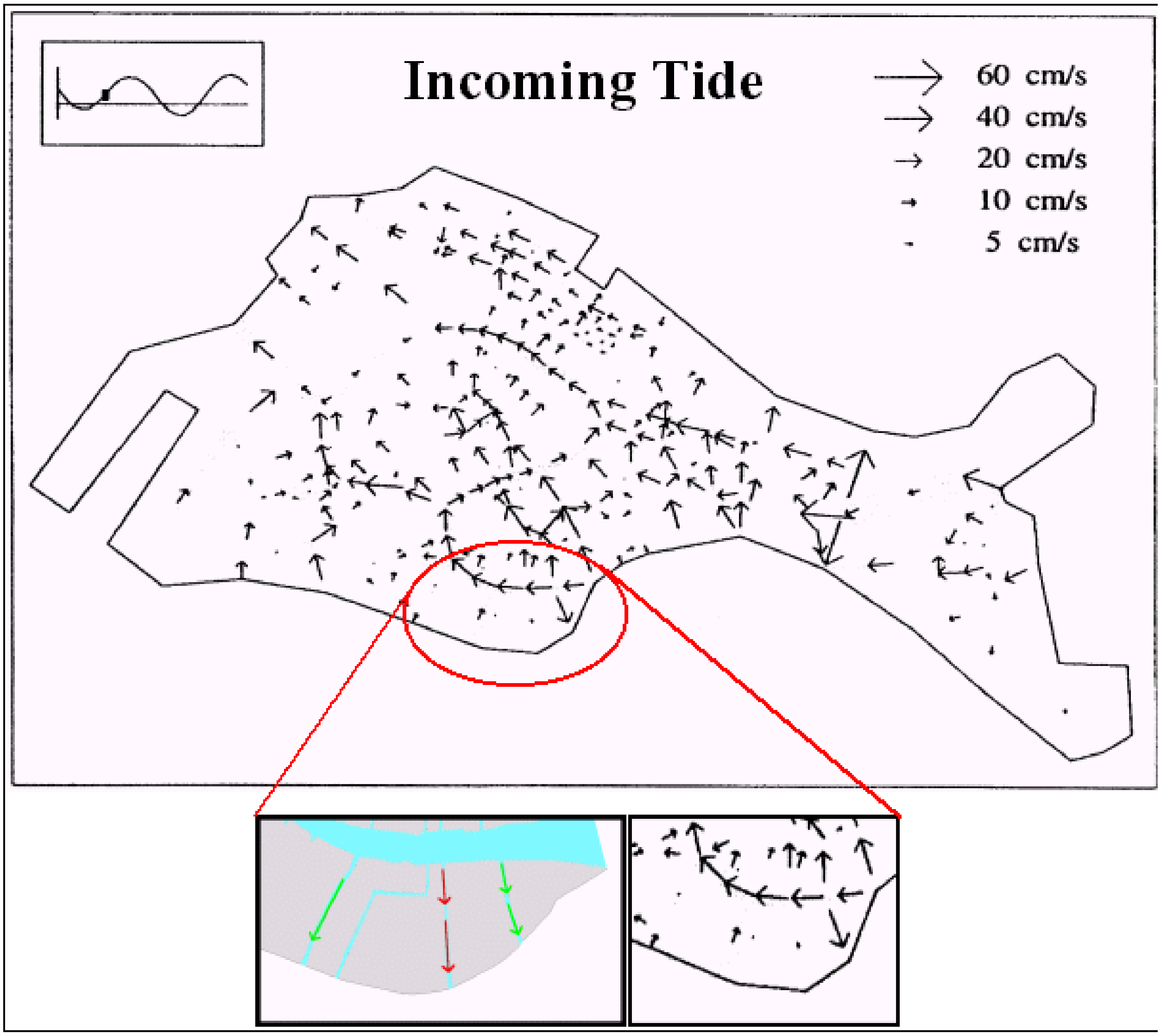


Figure 48: Flow model predictions for incoming tide vs. our data

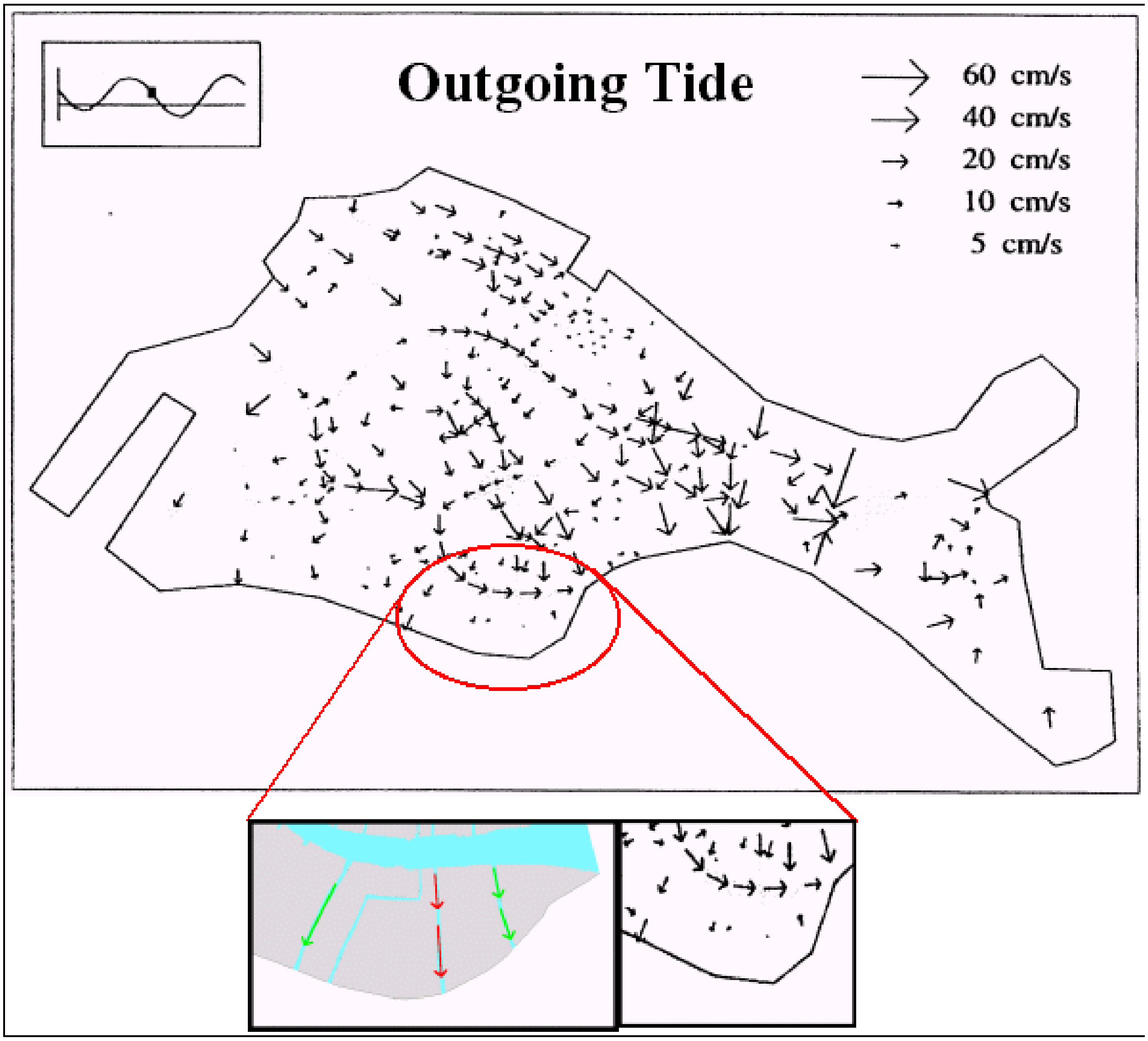


Figure 49: Flow model predictions for outgoing tide vs. our data

Chapter 8 - Conclusions

The purpose of this project was to complete the hydrodynamic characterization of the inner canals of Venice. Originally, we targeted 199 canal segments for which there were no previous flow velocity measurements. For various reasons, we were unable to measure 66 canal segments. To complete the characterization of the canals, future project groups will need velocity data for these canal segments in addition to those of the *Canal Grande* and the *Arsenale*.

Our velocity data was divided unto four speed ranges for incoming (Figure 50)

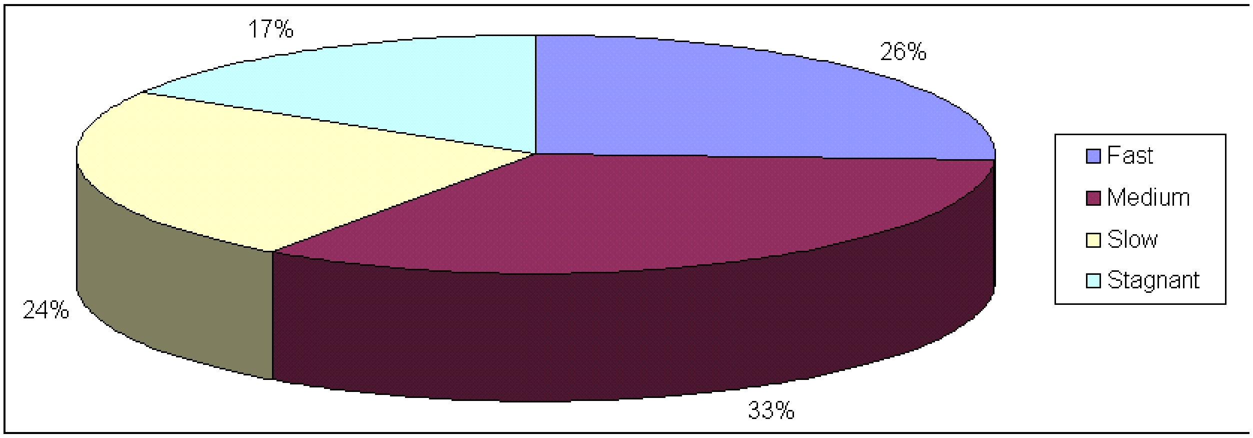


Figure 50: Percentage breakdown of flow speeds during incoming tides

and outgoing tides (Figure 51): stagnant ($0 \leq |v| \leq 1$), slow ($1< |v| \leq 10$), medium ($10< |v| \leq 20$), and fast ($|v| >20$).

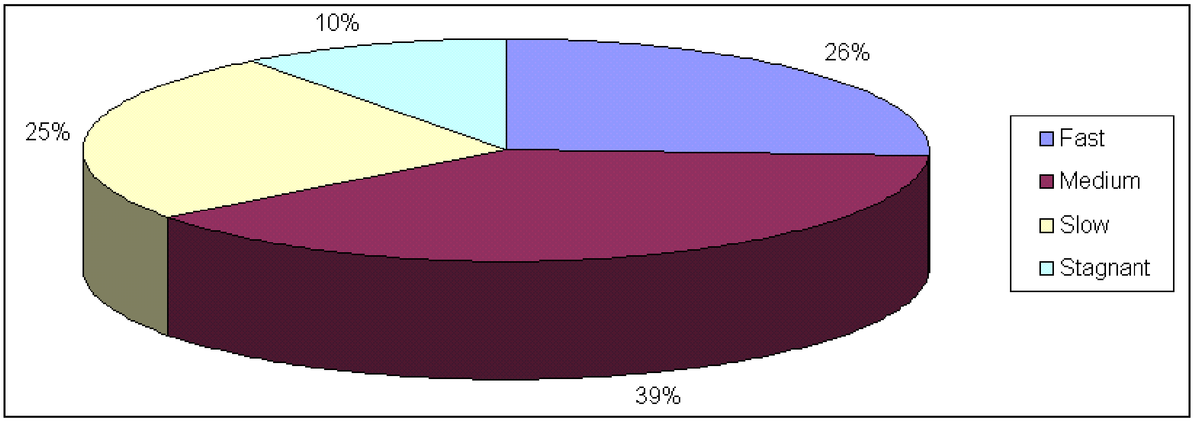


Figure 51: Percentage breakdown of flow speeds during outgoing tides

We combined our maximum velocity data with sediment accumulation data that was collected by previous WPI project teams. An extremely loose correlation was found between the amount of sediment accumulated in a canal and the velocity of the water flowing through it. However, once we took into consideration the length of the canal segment as well, a stronger relationship between the velocity of the water and sediment accumulation was observed. To describe this relationship, we calculated the Flushing Index of each canal segment, which was used to qualitatively describe the flushing capacity of water flowing through canal segments. We observed that those canal segments with higher Flushing Indices had lower amounts of sediment accumulation than those with lower Flushing Indices. Therefore, the water flowing in those segments with lower Flushing Indices is less effective at removing sediment.

Our maximum flow velocity data will serve two main purposes. The first is that they will be used to verify a sedimentation model that is being developed by ISDGM-CNR. Scientists have created the model in an attempt to correctly characterize the flow of the water through the canals of Venice, and to be able to predict how the behavior of the water will change if a canal is blocked off for dredging. Our flow data collected from the canal segments affected by dredging will prove especially helpful in determining if the model is capable of making correct predictions of flow behavior.

The second use of our data is that it will be part of the information considered by Insula with regards to the scheduling of canal maintenance. Use of the Flushing Indices will help determine through which canals the water flow is ineffective at removing sediment, and thus will require more frequent maintenance. This knowledge will help in the development of a long term maintenance schedule that will help prevent damage to building foundations and banks of canals. This in turn will decrease the amount of time it takes to dredge a canal, which would ultimately keep costs at a minimum.

A planned maintenance schedule would also be very useful to the citizens of Venice. Residents will be able to prepare in advance for the many inconveniences caused by the blocking off of canals. Long term scheduling would allow for alternate traffic routes to be devised and for different boat mooring locations to be arranged. Furthermore, the citizens will benefit because emergency boats will no longer be hindered by canals that are too shallow to allow boat passage due to sediment accumulation. Finally, there will be fewer health risks from the canal water because it will be more sanitary once the sediment is removed.

Chapter 9- Recommendations

Of our 199 initially targeted canal segments, we were only able to collect data for 110 that were not affected by dredging. This means that there are still 66 canal segments in addition to the *Canal Grande* that need to be investigated with regard to flow velocity. The following sections include our recommendations regarding these canal segments.

9.1 – Canals Being Dredged and Affected by Dredging

Dry dredging of canals is vital for completely repairing damage to canal walls. Due to canal maintenance occurring at the time of this project, six canal segments were completely empty of water and therefore no measurements were made for these segments. In addition to these canals being dredged, 23 of the immediately surrounding canals were also affected by the maintenance work. This was because when a canal is being dredged, the flow of water surrounding the blocked off canal will be different than when there is no work being performed.

For the purposes of collecting comparable data it is necessary that canals currently being dredged as well as canals we determined were affected by dredging be measured using our methodology. This will give important information concerning the effect that the closing and opening of canals has on the overall flow of water through Venice.

9.2 – Measuring Unreachable Canal Segments

Most of the canals that we could not measure were inaccessible because they did not have bridges or walkways, which made it impossible for us to make flow velocity measurements using our methods. A modified methodology needs to be developed that would make it possible to access the canals by different means. One possible way of accessing these segments is to use a boat from which measurements could be taken.

9.3 – Additional Sediment Accumulation Data

To produce a more complete analysis of the correlation between sediment buildup and flow velocities of canal segments, it is necessary that the collection of sediment data be completed. This analysis could further identify the areas that will need dredging more frequently than others.

Bibliography

Alberotanza, L. e Dazzi, R. (1970), *Descrizione del Percorso all'Interno di Venezia Seguito da una Macchia di Colorante Immesso in Canal Grande*, Consiglio Nazionale delle Ricerche, Istituto per lo Studio della Dinamica delle Grandi Masse, Nota Tecnica TN-12, Venezia, Ottobre 1970, pp.4.

Analysis of Sewer Holes and Canal Wall Damage in Venice, Italy (July, 1998). Venice E99 Materials CD-ROM.

Annual Activities Report. UNESCO Venice Office, 1997.

Baker, Brian A., Beavis, R., Corey, J, Curria, S., Kirkos, G., Newton, B., Nicolazzo, M., Ormond, P., Zoladz, Glen. A Static and Dynamic Study of the Canals of Venice, Italy (C'92), WPI IQP.

Carvajal, Hernando, Federico, M., Gonzalez, C., Johnson, T., Levesque, Jeff. The Study of Tide Flows, Mud Buildup, Boat Traffic, and Structural Damage on the Cannaregio Canal Subsystem (D'91), WPI IQP.

Ciacciarelli, Michael, O'Connor, B., Sylvia, B., Testa, Steven. A Hygienic, Dynamic, and Static Study of the Canals of Venice, Italy (C'90), WPI IQP.

Cioffi, Carlo M., Dulac, V., Marsano, J., Reguero, Roberto. Development of a Computerized Decision Support System for the Scheduled Maintenance of the Inner Canals of Venice (July 1997), WPI IQP JFZ VP04.

A Comprehensive Review of the Worcester Polytechnic Institute Venice Canal Studies (D'93), WPI IQP.

Comune Di Venezia. *Centro Previsioni e Segnalazioni Maree.*Venice, 4090 San Marco, 1999.

Comune Di Venezia. *Previsioni delle altezze di marea per il bacino di San Marco e delle velocità di corrente per il Canal Porto di Lido - Laguna di Venezia,* 1999.

Dorigo, Livio (1966), *Rilievi Contemporanei di velocità di marea nei canali della Giudecca, Fondamente Nuove, Canal Grande ed alcuni rii interni della città*, Ist. Ven. Sci. Let. ed Arti, Vol. III, Rapporti e Studi, Venezia.

"EPA Global Warming: Impacts-Coastal." Environmental Protection Agency, Internet, World Wide Web. http://www.epa.gov/globalwarming/impacts/coastal/index.html, April 15, 1999.

Fabris, C. (1937), *La Marea nei Canali di Venezia*, Ateneo Veneto, Atti della XII riunione, Sezione di Scienze, Venezia, 21 Marzo 1937, pp. 187-188.

Lane, Frederick. *Venice: A Maritime Republic*. Baltimore: Johns Hopkins University, 1973.

"Medex Winds." Naval Research Laboratory, Internet, World Wide Web. http://www.nrlmry.navy.mil/~medex/tutorial/medex/winds/wind_all.html, April 12,1999.

"Orbits." Nick Strobel, Internet, World Wide Web. http://www.bc.kern.cc.ca.us/programs/sea/Astronomy/gravappl/gravapplb.htm, April 4, 1999.

"Our Restless Tides, Chapter Three." Center for Oceanographic Products and Services, Internet, World Wide Web. http://www.opsd.nos.noaa.gov/restles3.html, April 11, 1999.

"Our Restless Tides, Chapter Four." Center for Oceanographic Products and Services, Internet, World Wide Web. http://www.opsd.nos.noaa.gov/restles4.html, April 11, 1999.

Our Restless Tides, Chapter Five." Center for Oceanographic Products and Services, Internet, World Wide Web. http://www.opsd.nos.noaa.gov/restles5.html, April 11, 1999.

A Static and Dynamic Study of the Canals of Venice, Italy (March 1993), WPI IQP.

A Topological and Hydro-Dynamics Study of the Canals in the San Marco (D'92), WPI IQP.

A Topological/Hydro-Dynamics Study and Geographical Information System of the Canals in the Castello Area (E'92), WPI IQP.