The Moto Ondoso Index: Assessing the Effects of Boat Traffic in the Canals of Venice

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By

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David Chiu

____

Anand Jagannath

____

Emily Nodine

Approved:

______________________ ______________________

Fabio Carrera, Advisor **David DiBiasio, Advisor**

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Natalie Mello, Advisor

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Authorship Page

This project was completed with the equal participation of each team member. Without full cooperation and effort provided by each team member, this project could not have been successfully completed.

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Abstract

This project, sponsored by the Consorzio Trasportatori Riuniti Veneziani, and *Pax in Aqua*, located in Venice, Italy created an index for ranking the energy level of each canal segment in the Venetian canal system. Boat traffic in the canals produces wake that erodes and destroys the walls of the canals, causing structural problems to the city. Wake heights of different boat types were measured, and the energy released by these wakes was calculated. The index was then created by assessing canal traffic patterns combined with the amount of energy released by different boat types when traveling at different speeds with different payloads. Additionally, this project suggested new traffic regulations that would reduce the total amount of energy in the canal system, and analyzed how probable traffic pattern scenarios would affect energy levels.

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Executive Summary

Every densely populated city in the world has a problem with traffic, and Venice is no exception. Venetian traffic, however, is different than traffic in any other city as it is composed of boats that travel in an extensive canal system. Rowboats were traditionally used for the transportation of people, goods, and waste. After World War II, technology in the rest of the world advanced and Venice followed suit by making use of motorboats as a faster and more efficient means of transportation. Although motorboats have brought speed and efficiency to the Venetian lifestyle, the powerful motors caused a new problem that the city had never faced before, *moto ondoso*[1]. The canal walls were designed and built long before motor boats were invented, and were therefore not intended to withstand the force produced by boat wakes. Now that motor boats are the main form of transportation in the canals, the walls are continuously pounded upon by the waves that these boats produce. The constant stress that the canal walls are subjected to causes them to erode and slowly fall apart. Since the canal walls also serve as the foundation to the buildings of the city, this destruction is not only expensive, but dangerous. This project was conducted in an effort to provide a system of assessing canal wall damage caused by canal traffic. With this system, the city of Venice will be able to efficiently reduce canal wall damage caused by boat wakes through the implementation of effective traffic regulations.

Venetian Boat Traffic

As a boat moves through the water it creates underwater turbulence that is caused by the spinning of propellers. Wake is the portion of turbulence that is visible on the surface of the water. Wake and turbulence create impact

Wake Produced by a Personal Boat

[1] *Moto Ondoso* can be roughly translated to mean "wake impact".

between the water and the canal walls, weakening and eroding them, causing a need for constant repairs. If a damaged wall goes too long without proper repairs the results can be dangerous. Some of these walls have been damaged so severely that they develop large holes and collapse, causing the buildings they support to collapse into the canals they border. Other factors, such as clogged sewer outlets, boat collisions, and biological and chemical agents intensify the effects of moto ondoso by weakening the canal walls. Once a wall has been weakened or damaged it is more susceptible to the erosive powers of the water, and is therefore destroyed at a much faster rate.

Moto ondoso is a prominent topic in Venice's current events, and constantly causes conflict. Articles about issues related to this debate appear nearly every day in the local newspapers. During our stay in Venice the team met with two organizations with opposite perspectives on the problem of moto ondoso and what should be done to alleviate the problem. Paolo Lanopoppi, the elected head of the anti wake organization *Pax in Aqua*, firmly believes that moto ondoso is the primary cause for canal wall damage and the destruction of the city's foundations. He believes that unless moto ondoso is drastically reduced, Venice will be in great danger. Ivano Turlorn is the Director of Technical Operations at Insula, the company who repairs and maintains the canal walls in Venice. Those at Insula believe that since canal wall damage is caused by a complex combination of many factors; there is no way to tell how much, if any damage is attributable to moto ondoso. Insula also believes that moto ondoso will always exist, so it would be more effective to create walls that are more resistant to wakes. The Venetian canal walls were not designed to withstand the force of boat wakes, so the original method of canal wall construction is outdated for the modern lifestyle that Venetians have adopted. A more modern, reinforced, canal wall construction would be resistant to damage. These conflicting views are the cause of constant debate on how to alleviate the problem of moto ondoso.

The City of Venice has made an effort to reduce the amount of boat wake and canal wall damage in a variety of ways. For instance, speed limits have been assigned to the entire lagoon. The only place these speed limits are currently enforced, however, is in the Grand Canal, so there is consistent speeding by boats traveling throughout the rest of the city. Since there is little enforcement of speed limits, the residents of Venice as a whole do not follow the recommended speeds. Reducing boat speed through the enforcement of speed limits would reduce the size of the wakes the boats produce and ultimately slow the speed at which the walls are being destroyed. Traffic restrictions have also been applied to canals suffering severe damage in order to slow the damage and prevent it from becoming a serious problem before it can be repaired.

To develop a system to objectively quantify activity in the canals, we developed a methodology that determined total energy released by boats into the canals. First we selected canals that were suitable for data collection. These canals were selected based on previously determined criteria. Through research, the team determined that the necessary information for determining the energy released by a boat into the water was the amplitude and period of a wave. During data collection we measured the amplitude and period of the wake produced by a given boat, as well as the boat's velocity. The type of boat and payload were also recorded. All data was taken on straight canal segments to ensure that wake size was an accurate representation of the amount of turbulence the boat was creating, as well as to avoid changes in speed so that accurate speed measurements could be made. With the values for wake height and wavelength, we calculated the amount of energy released into the canal by each recorded boat.

To determine the total amount of energy released into each canal segment a Moto Ondoso Index was created. This index is a summation of the energy value of each boat that passes through the canal segment each day, according to traffic data collected in past projects. An original index point value was calculated for each canal segment included in the study.

We determined that the height of the boats wake increases exponentially as speed increases. For example, a small cargo boat traveling at 5 km/h would produce a wake around 2 cm high. If the same boat were to speed up to 10 km/h the height of the wake would increase to almost 15 cm. The data also revealed that very few boats travel within the posted speed limits. The average speed in all boats in all canals was over 12 km/h, which is more than 7 km/h over the legal maximum speed. If boats were to travel within the speed limits, there would be a drastic decrease in the heights of boat wakes and therefore much less erosive water motion. Enforcing speed limits would greatly reduce the problem of Moto Ondoso.

For all boat types, the energy released increases as the speed increases. On average, small cargo boats release the most energy per passage, making them the most harmful to the canal walls. Taxi boats released the next highest energy level per passage, and vaparetto released the least.

We also examined how a boat's payload affects the wake it produces. When examining data of cargo boats with different payloads we found that wake height decreased as payload increased therefore, decreasing the amount of energy they released. A possible explanation for this trend is that when maneuvering long straight sections of canals (such as those used for data collection) heavy boats can rely on the momentum of the boat, rather than the motor to propel them. Since little force is required to keep the boat moving, the motor does not produce a large wake.

During data collection we made observations about different hull shapes of boats. We noticed that boats with narrow, streamlined hulls produced far less wake than those with boxy, square hulls. Regardless of boat type, boats with boxy hulls would therefore cause more damage to the canal walls than their sleek counterparts.

To analyze the data, base Moto Ondoso Index values for winter and summer were calculated for each boat type using energy values of these boats traveling at the 5 km/h speed limit. Indexes of different traffic scenarios were then calculated and compared to this base value. The total base index for the summer months is 42% higher than in the winter months due to the increase in number of tourists. The indices were then broken down by boat type, and at the actual average speed that boats currently travel in the canals, small cargo boats release by far the most amount of energy into the canals (66%), however if all boats were to travel at the posted speed limit of 5 km/h taxi boats would be responsible for most (53%) of the energy released. We also made a projection about how the index for the canal system would change if all boats were to travel within the speed limits. At the speeds boats currently travel in the canals, they release more than nine times the amount of energy they would if they were to travel within the speed limits, causing over nine times the amount of damage they are supposed to. Speed limits are currently loosely enforced in the canal system through the use of laser guns that clock boat speed, and a system of consequences that include boat confiscation. If this method of enforcement became stricter, the excessive speeding would be reduced, causing a drastic decrease in wake energy and the canal wall damage rate.

Other applications of the Moto Ondoso Index included projections of the effect of increased taxi boat speed limits and the reduction of cargo boat traffic. Taxi boat drivers are attempting to convince the city of Venice to change their speed limit from 5 km/h to 7 km/h within the inner canals. Increasing the index of taxi boat travel only 2 km/h from 5 to 7 would cause their index value to increase by 80%. However on average, taxi boats already travel above 7 km/h, so it likely that if their speed limit were to go up they would increase their speed even further causing an even greater increase in the amount of wake energy they release. A project completed last year proposed re-engineering the cargo delivery system in Venice in way that would reduce the amount of cargo boat traffic by 90%. If boats were to continue traveling at their current speeds, the 90% cargo boat traffic decrease would lead to a 68% decrease in the total Moto Ondoso Index for the canal system, causing a drastic decrease in the total energy of the canal system. The implementation of this plan would relieve a substantial amount of canal wall damage due to wakes.

Every year the amount of canal traffic increases around 2.5%. We made projections of how the total indexes would change if the traffic flow were to continue increasing at the current rate. In the next 5 years the total index would increase by 13% and in ten years the index would increase by 28% of the current index. Therefore there by 2012 there will be 28% more energy being released into the canals than there is currently, causing the wall damage rate to increase further, and more rapidly as time goes on.

Our project has not only determined the primary causes of wake damage in the canals of Venice such as excessive speeding and an inefficient cargo delivery system, but suggested methods of alleviating these damaging factors. If boat speed was reduced by a more widespread enforcement of speed limits, and the cargo delivery system was redesigned, the effects of moto ondoso on the city of

Venice would be far less severe. We have also designed powerful tool that the city a tool that the city can use in the future. The Moto Ondoso Index system gives insight on how the canal walls might be affected by any changes in traffic flow or any proposed traffic legislation. Since the index encompasses variables such as traffic, speed, payload, and season, it becomes a multi-faceted tool that can be used to make effective changes that will decrease the dangerous effects of moto ondoso.

1 Introduction

Venice, Italy, one of the world's most famous cities, is well known for its beautiful art, quaint cafés, romantic gondola rides and most of all the canal system. The common person however is not aware of Venice's dangerous situation. For years, Venice's foundation has been continuously pounded and eroded by the wakes of motorboats traveling in and around the city. If this rate of the destruction persists, Venice's beauty will continue to disintegrate. Every year, twelve million tourists visit Venice and try to absorb its beauty and culture as they sit in cafes gazing at St. Marks Basilica, and float through the canals in gondolas; but most are completely oblivious to the fragile state of the city. They will leave within a short period of time and return to their normal life with only fond memories of their stay in the romantic city.

The residents of Venice, however, are constantly reminded of the continuous erosion of their city caused by moto ondoso, or wake impact. Articles on issues related to moto ondoso appear in the headlines of the local newspapers multiple times a week. Crumbling bricks and collapsing bridges are visible through the city, and damaged walls are shielded from the erosive canal water by temporary sections of iron sheeting. The locals are the ones who are most greatly affected by the disintegration of the city for it is their home that is being destroyed. Unlike the visitors, if the city crumbles the locals are left with no place to live. The threat of the moto ondoso or wave impact phenomenon is common knowledge to all Venetians, but as a whole they have not taken action to save their home from destruction.[2]

The canals in Venice are used extensively for transporting people, food, supplies, cargo and garbage. After World War II, Venice began to embrace modern modes of water transportation by introducing motorboats into its canals. Motorboats produce wakes of varying sizes and strengths. In the open sea these wakes disperse over vast, open areas, but in a confined area such as the Venetian canals these boat wakes wash up against the canal walls causing erosion. Boat wakes, however, are not the sole source of damage to the city's foundation. Venice's sewer system consists of underground pipes, which empty into the canals. The sewer outlets on the canal walls are sometimes blocked by silt that has built up over the years on floor of the canal. Sewage gets backed up in the pipes behind the walls and eventually must find a different way to exit the sewer system. The sewage is forced through the mortar that binds the building materials, weakening the structure and thus making the wall more susceptible to the erosive powers of the water. Biological and chemical materials such as sulfuric acid, pollution and algae also weaken the walls by expediting the disintegration and erosion of the walls.

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[2] Zwingle, Erla. Italy's Endangered Art, "National Geographic" pp 90 Aug. 1999

Canal wall damage causes widespread inconveniences for all Venetians. The city is forced to spend money to repair and restore the damaged walls. The money for these repairs comes directly from the taxpayers, making Venice an expensive city in which to live. The damage greatly impacts those whose houses border the canals. The canal walls serve as the foundation for these residential buildings, and when it is damaged the buildings sometimes fail die to structural instability. Personal residencies are not the only buildings that border the canals; local businesses and shops also suffer from the damage. If the city of Venice could reduce canal wall damage, the money that would otherwise spend repairing the walls could be used for funds focusing on other social issues.

The ultimate goal of this project was to provide Venice with a system of assessing the amount of wall damaging energy that is released into each canal segment by boat traffic through the completion of the following objectives: measuring the wakes of different types of boats, calculating the total energy released by boats into the canal system, and creating a representation of the amount of energy that is released into each canal segment by the current flow of traffic. With this system we then determined the impact of variations in the current flow of traffic.

The remainder of this report includes Chapter 2: Background, which provides information on moto ondoso and the impact it has on Venice, and the information on the Venetian canal system. The Methodology, Chapter 3, discusses the steps taken in order to complete the project, including data collection, sample calculations, and analysis. The information obtained through data collection and research is discussed in Chapter 4, and Chapter 5, the analysis section, discusses how the collected data was interpreted. Finally, the team's Conclusions drawn from the analysis are provided in Chapter 6 along with Recommendations which provide actions that the city could take to alleviate the problems caused by moto ondoso.

2 Background

This project studied the damaging effects of boat wakes in the canals of Venice. To do so, the team researched some general background information about wakes, boats, and Venice. This chapter contains all the important topics that are relevant in the study of Moto Ondoso.

2.1 Transportation in Venice

Since the waterways of Venice are analogous to the paved roads of other cites, Venetians are dependant on the canals for distribution of goods and transportation of people around the city. The canals also play a major role in the waste disposal system of Venice. The canals divide Venice into more than 100 islands all of which need to be accessible by boat. Services such as garbage collection and ambulances need the canals to access these islands. The economy of Venice is greatly dependant on the tourism industry, which relies heavily on the canal system because it is used extensively for tourist transportation and sightseeing.[3] The heavy use of the canals by boats creates problems with traffic and congestion, which will eventually lead to canal wall damage.

2.1.1 Canal Traffic

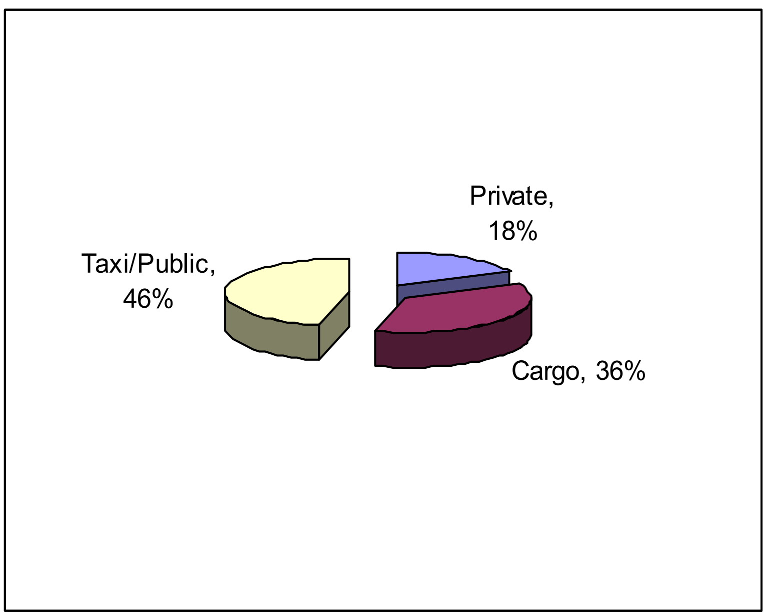

Figure 2-1 Canal Traffic Makeup[4]

Since their introduction into the city of Venice in the late 1950's, motorboats have become the primary form of transportation. Tasks once performed by rowboats are now mostly carried out by motorboats, including the transportation of cargo and people. As a result of this, wakes increased considerably.

The traffic of Venice is made up of many different types of boats. Figure 2-1 shows the makeup of the

[3] "Monitoring and Analysis of Cargo Delivery System in Venice, Italy" IQP. pg. 3-4
[4] Carrera, Fabio and Caniato, Giovanni; "Venezia la Citta Dei Rii"

traffic within the Venetian canal today. Cargo boats and taxis make up most of the water traffic.[5]

2.1.1.1 Boat Types

Figure 2-2 An Actv vaporetto

Figure 2-3 A parked taxi boat

The boat traffic in Venice is divided into three categories; boats used for transportation of people, transportation of goods, recreation, and special services.

Since many of the people in Venice are visitors, there is a large demand for public transportation. The system of public transportation in Venice is similar to systems found in other cities of the world. The Vaporetti shown in Figure 2-2 are the equivalent to a city bus in the United States. Vaporetti are large boats that follow set routes and carry many people at a time. Water taxis, which pick up passengers at special docks around the city, are much like their land counterparts. A standard taxi boat is shown in Figure 2-3. For large groups of people, the Gran Turismo can be chartered in the same way as a bus would be on land.

Goods are transported through the city by cargo boats. Cargo boats are grouped into three sizes: small, large, and construction boats. Figure 2-4 is an

Figure 2-4 A small cargo boat

Figure 2-5 A large cargo boat

[5] "The Optimization of Cargo boat deliveries Through The Inner Canals of Venice" IQP. pg. 3-5

Figure 2-7 A construction boat

Figure 2-6 A garbage boat

example of a small cargo boat (have outboard motors) and Figure 2-5 is an example of a large cargo boat (have inboard motor and a separate area for steering). Construction boats, as shown in Figure 2-7, are often equipped with cranes that assist in unloading heavy materials. Garbage boats (Figure 2-6) travel the canals every day but Sunday to collect solid waste from all around the city.

Figure 2-8 A personal boat

Boats used for recreation include personal boats and gondolas. Personal boats (Figure 2-8) are owned by residents of the city and used as an alternative to public transportation and for pleasure. Gondolas are used primarily by tourists for light transportation and for touring of the city rather than as a serious form of transportation. Figure 2-9 depicts gondola giving tourists a ride through the Grand Canal.

Figure 2-9 A gondola traveling on the Grand Canal

Other motorized boats that travel in the canals of Venice include public service boats used by the city for postal service, emergency medicine, and police.[6]

[6] "Evaluation of Tourist Use of Venetian Transportation", IQP 2001. pp. 28-29

2.1.1.2 Boat Traffic Study

Between the dates of February, 1992 and July, 1994 WPI students completed projects that collected data on the traffic flow in several major canals in Venice. This study included a count of boat passages per day and included specifications on boat type and approximate payload. These studies were useful in conjunction with data collected on wake heights in making an estimate of total energy released into the canals by boat wakes. These studies were also useful to the team in creating an energy index for the most highly trafficked canals.

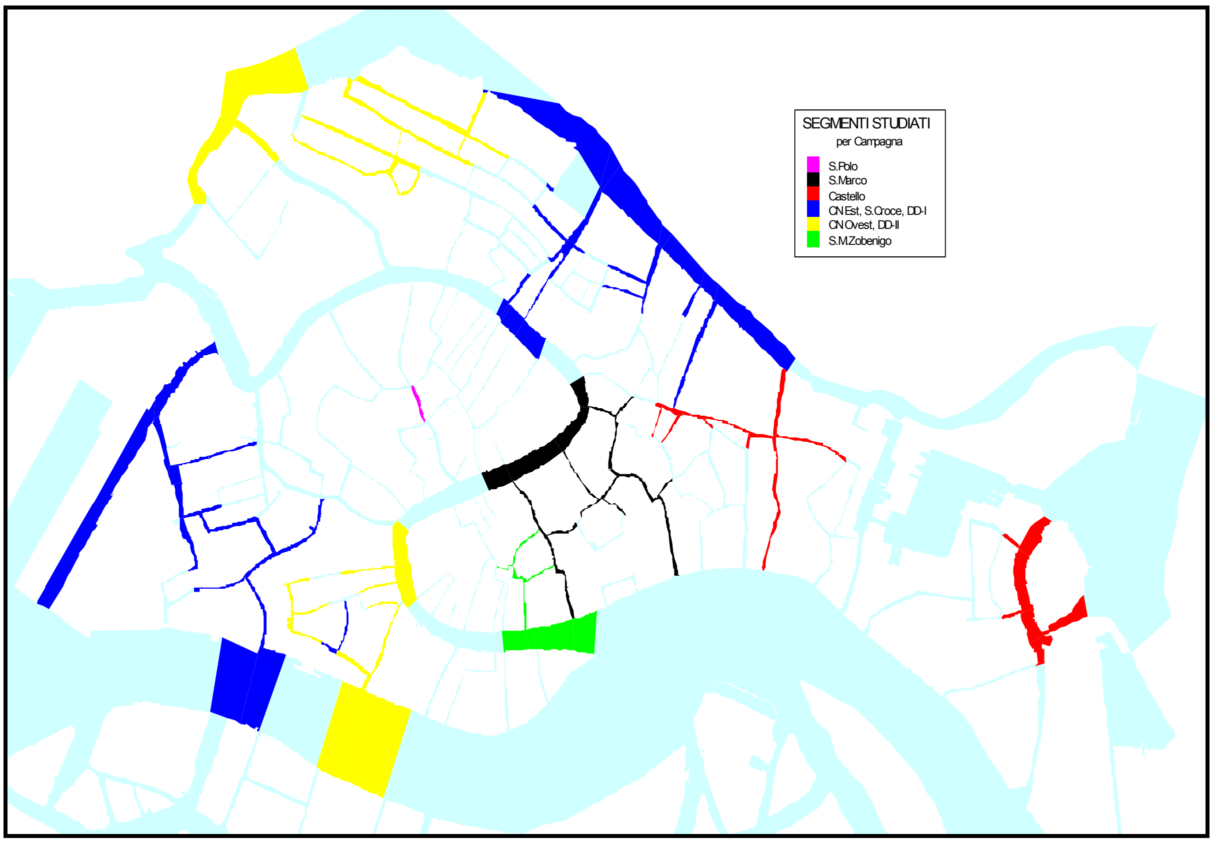

Figure 2-10 Canals segments evaluated in WPI traffic study[7]

[7] Carrera, Fabio; Il Traffico Acqueo Nei Canali Interni Di Venezia, 10, Luglio, 1996.

2.1.2 Canal Congestion

The large number of boats traveling in the canals is not the only cause of the traffic problem in Venice. The constant stop-and-go motion of various boats causes congestion, which is another traffic problem. The inefficiency of the cargo delivery system is one major source of congestion. Several cargo boats, each carrying a different item, stop at the same dock to make deliveries. This system results in crowding of the boat docks, which causes traffic jams in the canals (as shown in Figure 2-11). The implementation of the plan proposed in a WPI project completed in 2001[8] would organize cargo boats not by cargo type, but by destination. This would result in reducing the number of cargo boats in the canals by approximately 90% and relieve congestion.

Figure 2-11 Cargo boat congestion in a canal

Sightseeing gondolas also cause congestion in the canals. Many gondolas will sometimes stop or travel slowly in front of a scenic area all at once. Gondolas sometimes block an entire canal so that it is impossible for other boats to pass until the gondolas continue on their way. Another source of canal congestion is parking on the sides of canals. Boats in Venice are often double parked due to a lack of available spots. Parked boats make the canals even narrower and allow even less room for traffic to pass through, sometimes blocking the canals completely.[9]

The physical characteristics of the canals create obstacles which can lead to greater traffic congestion. Many of the larger, heavier boats ride low in the water and can not pass through the smaller canals because there is not enough water clearance. This restriction causes all of the larger boats to be rerouted to the large canals. Tides also play a part in the restriction of travel in the canals. During low tides the water level may be too low for many boats to pass, and during high tide larger boats may not be able to pass under the bridges that are scattered throughout the city. These obstacles force boats to remain in the main routes, ultimately creating more congestion.[10]

Congestion is harmful to canal walls in many ways. One reason is because boats must remain idle in the canals. Boat drivers must continually switch between forward and reverse drive motions in order to keep the boat in place. Secondly oncoming boats must break immediately due to the traffic stop ahead. In both these situations the propellers are continuously switching from

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[8] "The Re-Engineering of the City of Venice's Cargo Transport System" IQP, 2001
[9] "The Optimization of Cargo Boat Deliveries through the Inner Canals of Venice" IQP. pg. 3-4, 3-5
[10] "Monitoring and Analysis of Cargo Delivery System in Venice, Italy" IQP. pg. 3-4

spinning in a forward motion to spinning in a reverse motion which causes much turbulence underwater. It is this turbulence that causes much of the canal wall damage; this phenomenon is further explained in section 2.2.1 of this document.

2.2 Canal Walls

Figure 2-12 Canal Wall Construction: Type of Wall Lining for Fondamente

Traditionally the canal walls of Venice can be made of two different materials. The foundations of buildings and the lower parts of some canal walls are made up of Istria stone. This type of stone is non porous, so it does not allow water to penetrate, making corrosion almost nonexistent. Brick is generally used for construction on top of the stone. Fondamente are made entirely of brick as shown in Figure 2-12; Istria stone is rarely used. Brick is a popular building material because it is readily available and inexpensive, but since it is extremely porous, brick is easily corroded by the salt water of the lagoon. When repairing canal walls concrete is installed at very base of the walls for additional reinforcement. Figure 2-13 shows the materials used when repairing canal walls; concrete, Istria stone, and brick.[11]

Figure 2-13 Construction of Walls That Have Been Repaired

2.2.1 Causes of Canal Wall Damage

The deterioration of the canal walls occurs when their physical and mechanical conditions are altered. The turbulence in the water caused by boat wake is a major factor in the destruction of the canal walls because it slowly erodes the wall material or the mortar that acts as a seal between the bricks and stones. When the mortar erodes, the bricks and stone become disjointed and are thus much more susceptible to the destructive stresses and forces of boat wakes.

[11] Insula: http://www.insula.it/

When the use of stone in construction of the city of Venice began, the sea level was such that only the Istria stone sections of the canal walls were exposed to the water[12]. Due to the rising sea levels around the world and the sinking of the ground due to subsidence induced by the excessive water extraction from the aquifers underneath the city for industrial uses, the water level in the Venetian lagoon has risen by approximately 23 centimeters since 1897.

After the Second World War, the population of motorized boats in the canals of Venice increased rapidly, which caused further destruction to the canal walls because of the wakes produced by the motor boats.[13] Before motorboats were introduced into the canals of Venice, the canal walls were essentially only subjected to the forces of water as it flowed in and out of the lagoon with the tides. Because motorboats have since become the primary mode of transportation in the city, the canal walls have been exposed to the constant beating force of boat wakes. When the propeller of a boat spins in the water it causes turbulence which on the surfaces of the water can be seen in the form of a wake. Wake, shown in Figure 2-14, is the product of uneven pressure in the water which automatically attempts to regulate itself and become neutral. Before this steady state is attained, the wake of the boat comes into contact with the walls of the canal. Erosion, the most destructive force to the canal walls, occurs when water rubs against the surface of the canal wall, causing friction. Wake is incredibly destructive to the wall surface because it increases water turbulence, multiplying the erosive force of the water.

Figure 2-14 Boat wake

Imperfections in the wall surface, such as missing or chipped bricks, make the canal walls more vulnerable to erosion. When turbulence in the water comes into contact with a flat wall, it can only affect the surface area. Holes and uneven brick increase the surface area of the wall, allowing water to do more erosive work. Water will flow into the hole and instead of being reflected off, it will swirl around inside the hole. Sometimes a wall will appear to be almost flawless, but due to a missing brick or water has been entering and eroding behind the surface. Water currents then carry away the eroded pieces thus weakening the foundation. Over time the wall surface may still be intact, but the structure that lies behind the surface has been damaged and the entire wall may collapse.[14]

[12] Ibid
[13] "Monitoring and Analysis of Cargo Delivery System in Venice, Italy" IQP.
[14] UNESCO Website: "Venice, Safeguarding Campaign - Damages Caused by Swirling Water" (Accessed April 26, 2002) http://www.unesco.org/culture/heritage/tangible/venice/html_eng/menacemon.shtml

The canals in Venice are also a major component of the sewer system. Sewage flows from houses, in conduits under the streets, and eventually enters the canal through outlets below the waterline. Sediment builds up on the floor of the canals at a rate of up to two centimeters per year.[15]

Structural damage is caused by the sewer system when the silt levels get high enough to block the sewer holes in the canal walls. Since the sewage can not flow out of the pipes and into the canal, tremendous pressure builds up in the pipes housed within the canal walls. When enough pressure has accumulated the pipes will rupture and the sewage is rerouted to within the foundations of the canal walls and will eventually seep through the mortar, weakening the structure considerably. The damaged walls are more vulnerable to erosion from water and boat wakes.[16]

Collisions between boats and canal walls, and pollution are additional factors that make canal walls vulnerable to erosion. Collisions, which commonly occur at intersections and docks, create holes and chips in the wall surface. Pollution and sewage in the canal water help to corrode and decompose the mortar and brick. Once a small amount of damage has been done to the wall surface, the damage will only continue and become exponentially more severe. Chemical and biological materials also contribute to canal wall damage. Sulfuric acid damages stone when it interacts with the calcium carbonate in the stone, chemically changing it to calcium sulfate. In the case of the canal walls, the change in composition of the stone causes the interior structure to crumble. The source of the sulfuric acid comes from the Mestre-Marghera industrial zones, which were extremely active up until the end of the 1970s. Biological materials such as bacteria, fungi, seaweed, and lichens also cause the deterioration of the canal walls. These organisms eat away at the inner supports of the canal walls as well as the stone. The humid climate of Venice exacerbates this process since the warm, moist air promotes the growth of these organisms.[18]

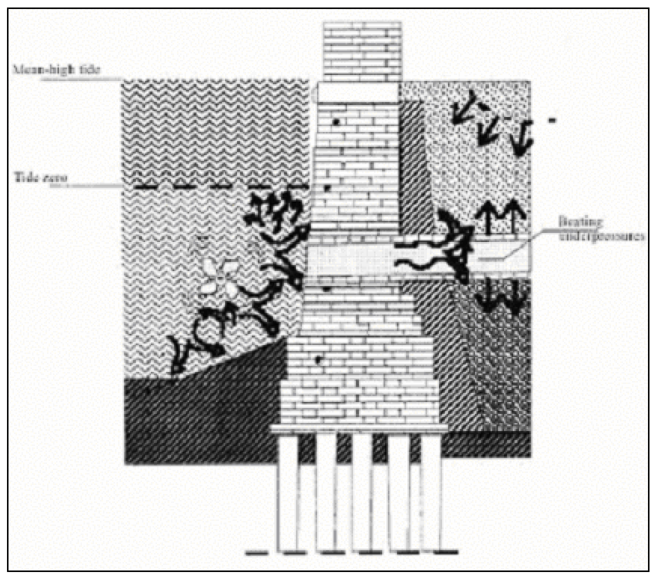

Figure 2-15 Causes of Canal Wall Damage: Water turbulence caused by motor boat propellers and pulsating underwater pressure[17]

Traffic congestion is also damaging to canal

[15] "A Preliminary Study of the Implementation of Hiflo Vacuum Sewage System Within The City of Venice" IQP, 1997. pg 3-5
[16] Ibid pg 3-6
[17] Insula: http://www.insula.it/
[18] UNESCO Website: http://www.unesco.org/culture/heritage/tangible/venice/html_eng/menacemon.shtml and http://www.unesco.org/culture/heritage/tangible/venice/html_eng/menacelag.shtml

walls because of the water turbulence caused by maneuvering. When breaking, boat drivers must put their engines in reverse to slow themselves down. Boat drivers alternate between the reverse and drive gears to remain in a constant position. This is more evident in taxi and cargo boats. This motion causes large turbulence underwater, which is damaging to the canal walls, as discussed in Section 2.1.2. Figure 1-9 a visual description of the underwater turbulence caused by boat propellers and examples of force vectors of the wakes that impact the canal walls.

2.2.1.1 Hydrodynamics of Boat Wakes[19]

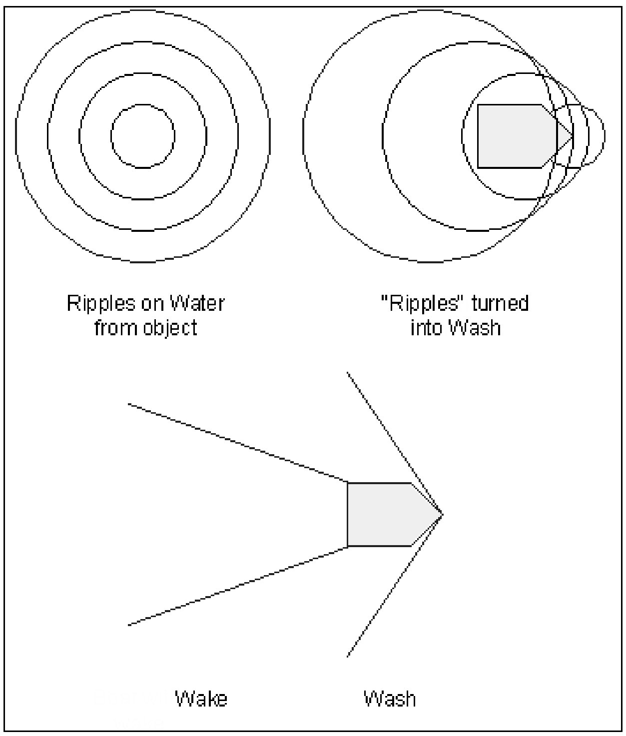

Figure 2-16 Origination of Wake and Wash

Physically, there is no way to move a boat through water without creating some sort of disturbance. There are two different waves created by motor boats: “wash”, which is created by the front of the boat pushing through the water, and “wake,” which is created by the boats propeller causing turbulence in the water. Wakes are the result of a physical body displacing water as it moves about. Think of the ripples on the surface of a body of water caused by an object being dropped into the water. When the object is moving across the top of the water it is continuously pushing this water aside causing more ripples, very similar to the Doppler Effect, in terms of boats these “Doppler ripples” are referred to as “wash”. “Wakes” are what come from the back of the boat; they are usually the after-effect of the turbulence caused by the boat’s propellers. The size of wakes can depend on many different factors such as: the speed of the boat, the size of the boat’s propeller, the power of the boat’s engine, the shape of the boat’s hull, the depth of the channel being traveled, and the boat’s load.

Because all boats are different and displace a different amount of water depending on the previously listed factors, it is very difficult to assign a specific wake size to a specific speed. A more

[19] “Watching Your Wake: A Boaters Guide” Oregon State Marine Board: http://www.boatwashington.org/watching_your_wake.htm

relative scale is necessary. There are three categories of relative speeds for boats and each speed category will damage canal walls to various degrees. The three speed categories are as follows:

1. Displacement Speed
2. Transition Speed
3. Planing Speed

"Displacement Speed" is a boat's slowest range of speeds. The boat is level with the water and there is minimal wake and wash created by the boat. Generally, when signs are posted calling for "no wake" this is the speed at which motor boats must travel to keep their wake down.

"Transition Speed" comes as the boat is accelerating through the water. Typically the bow of the boat is high out of the water, and this speed creates the largest amount of wake and wash, as the stern of the boat pushes through the water with the motor.

"Planing Speed" comes after Transition Speed when the bow of the boat returns to water level. Planing speed creates less wake and wash than Transition speed, but more than Displacement speed. Unfortunately many boats are not designed to reach this speed, and especially within the Venetian canals which are much too small and narrow for boats to able to reach this speed.

Underwater turbulence caused by the spinning boat propellers, not the wake, is one of the main causes of canal wall damage. In the case of the Venetian canals, due to their limiting widths and depths, this underwater turbulence is visually manifested by boat wake. When a boat in the lagoon or the open ocean there is a lot of area for the turbulence to disperse, but within the Venetian canals there is a limited depth and width, which causes all the energy to reflect back up to surface of the water. This unique situation is how the team will be able to effectively measure this damage caused by the normally unseen underwater turbulence. The energy created by the boat propeller in the water has no room to disperse, so the wake created is an accurate representation of what is happening within the canals. In Venice the team will be studying wake caused by boats traveling at displacement speed and transition speed.

Knowing the different types of relative boat speeds was important to the team as well as the Venetian people. This information will give the public a better understanding of what constitutes responsible boating, and will also give the project team a more realistic measure of which boats are traveling irresponsibly and which are traveling responsibly. For example, the team's data collection may find a certain boat type constantly traveling at a seemingly irresponsible speed, but actually, that boat type is not producing incredibly harmful wakes because it is traveling at displacement speed.

2.2.1.2 Energy of Boat Wakes

A study done in November of 1996[20] used a combination of kinetic and potential energy to determine the total energy a boat wake exerts on the walls of the Venetian canals. Total energy is based on the amplitude and wavelength of the wave, as well as the angle at which the wave moves away from the boat as shown in the equation below.

$$E = \frac{1}{8}\gamma H^2 L \sin\sigma \qquad \text{Equation 1}$$

In the stated equation, E is the total energy released into the water by the boat in kg-m (i.e. kg of force, as opposed to kg of mass), γ is the density of water in the Venetian lagoon (1024 kg/m³), H is the amplitude of the wave in meters, L is the wavelength in meters, and σ is the angle made between a perpendicular line from the rear of the boat and the leading edge of the wave as shown in Figure 2-17. The value of wavelength was calculated using the equation:

$$L = \frac{gT^2}{2\pi} = 1.56T^2 \qquad \text{Equation 2}$$

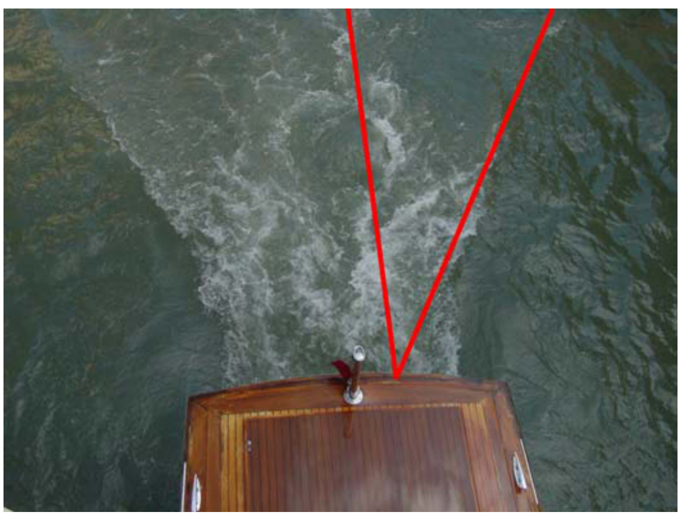

Figure 2-17: The Angle σ

Where g represents the acceleration due to gravity (9.81 m/s²) and T represents the period of the wave, or the amount of time the wave takes to complete one cycle in seconds. The angle σ was determined to be approximately $34.5°$ in the 1996 study and was the default angle used by the project team. These equations are derived in Appendix D. The team measured period and amplitude and used the data to calculate the energy released by passing boats.

In May of 1994 the Commune of Venice[21] completed a study on the wakes created by different boat types. In the study, boat types commonly found in Venetian canals were emptied of

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[20] Personal correspondence with Sergio Vazzoler, author of "Moto Ondodo Nei Canali Di Venezia", July, 2002. And, Vazzoler, Sergio and Canestrelli, Paolo, "Moto Ondoso Nei Canali Di Venezia" ATTI: Classe Di Scenze, Fisiche Matematiche E Naturali; Instituto Veneto Di Scienze, Lettere Ed Arti; 1996

[21] Assessorato ai Trasporti e Servizi Pubblici Commissione per lo Studio Del Moto Ondoso; Commune di Venezia, May 1994

all payloads and taken into the lagoon. Boat drivers were instructed to travel at the different speed limits set throughout the lagoon and the inner canals. Wake height was measured and tables were compiled that compared boat speed to the wake height and graphs were created to show the relationship of the two variables. The graphs showed an exponential growth of wake size as boat speed increased. Figure **2-18**, an example of one of these graphs, shows the relationship between speed and wake size of a motoscafo taxi. However, the project team was interested in the boats that travel in the inner canals and those boats do not typically obey the speed limits except for in the Grand Canal where they are strictly enforced. Therefore, the data collected by the team exceeded the

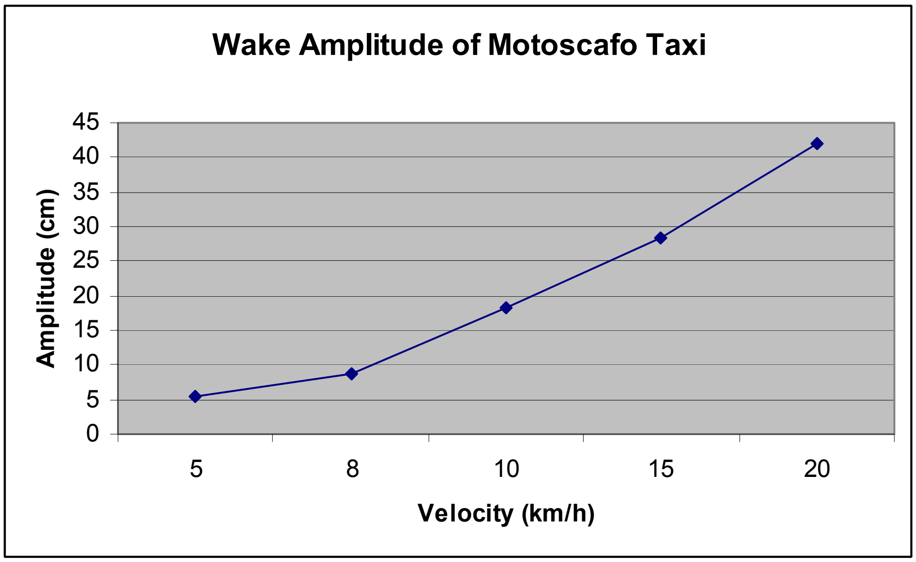

Figure 2-18 Wake height vs. velocity of taxi boat[22]

bounds of the data in the study. Since the data graph showed an exponential growth in wake size, the team used the study as guide to see if the collected data followed a trend similar to that found in the study.

2.2.2 Effects of Canal Wall Damage[23]

In December of 1990, a large cavity was found behind one of the walls of the Rio Novo. Although there was only a small hole at the surface of the wall, water had discretely eroded the supporting structures behind the wall, and it was on the verge of collapse. When Rio Novo closed, boats traveling in the direction of Piazzale Roma were rerouted to Rio Cerris. Within two years a building housing condominiums close to the Ponte Rosso completely collapsed due to the moto

[22] Commune di Venezia: Assessorato ai Trasporti e servizi Pubblici Commissione per lo studio del moto ondoso, May 1994.
[23] Testa, Silvio, Il Gazzettinno, 2001.

ondoso from the increased traffic flow. Rio Cerris had become a taxi highway, and the constant water motion these boats caused destroyed the foundation of the building beyond repair. The twelve owners of the building, in addition to losing their homes, were fined for failing to make repairs on an endangered building. Finally, after seven years and 7 billion euros worth of work, Rio Novo was reopened to taxi boats in 1997.

Another incidence of building collapse took place 1994 in the one way canal, Rio Dei Greci. The canal was closed for a period of time and was then reopened to traffic when a building collapsed from wake erosion from excessive traffic.

The Grand Canal is always a major traffic route, so buildings that line the canal are constantly subjected to moto ondoso. In 1995 Ca' Foscari was in risk of collapse and closed. The building is still under renovation.

After years of construction, the Galeazze Canal near the Arsenale was reopened to taxi boats. After only two years the walls were badly damaged so metal sheeting was installed along the wall as a blockade. Within a year of this installment, in 1999, the entire canal was closed to boat traffic due to the rapid rate of wall destruction. Other canals that have been closed to traffic because they, or the buildings that line them are in danger of collapsing include Rio della Maddalena, San Moise, San Lorenzo, and the Rio del Noal.

Moto ondoso is not only destructive within the city, but in other areas throughout the Venetian Lagoon. The City Hall on the Lido had to be evacuated and closed in fear that it would collapse. The cemetery island is in a high traffic area of the Venetian lagoon, so it is also vulnerable to moto ondoso. One billion euros have been spent by the Magistrate of Waters to fix and reinforce the Codussi chapel on the cemetery island that was destroyed by the lagoon water motion.

2.2.3 Preservation of Canal Walls

The problems caused by destruction of canal walls are not going unnoticed. If the current rate of destruction continues, the deleterious effects will be felt by all Venetians. Those who live directly on the canals will especially suffer from the structural instability caused by the damage to the canal walls which serve as the building foundation. Efforts are being made to preserve canal walls that are still intact and repair and reconstruct those that have suffered severe damage.

2.2.3.1 Damage Prevention

The best method of saving the canal walls and the lagoon is to prevent damage from occurring, or at least slow the rate of damage. Speed limits have been set throughout the lagoon: 20 km/h (orange) in the Giudecca canal, 7 km/h in the Grand Canal (yellow), and 6 km/h ((light blue) in other large canals as shown in Figure 2-19.

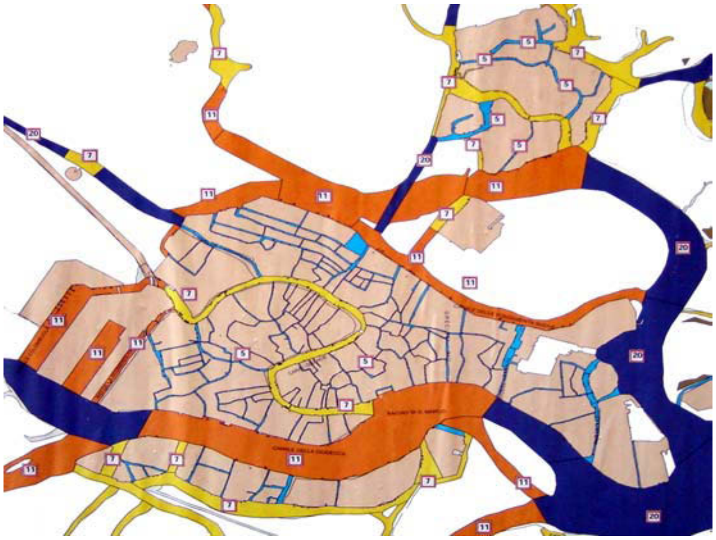

Figure 2-19 Color Coded Speed Limits in the Historical Center[24]

Speed limits are enforced by a central task force made up of seven local area forces as well as the Coast Guard. This collaboration agreed on penalties that would apply to the entire lagoon in order to create consistency and avoid confusion of regulations. Police boats track speed with radar guns in order to enforce these limits. Since the previous system of fining speed limit violators proved ineffective, more threatening punishments were implemented. Those who are caught exceeding speed limits have their boat is confiscated for a week for the first offense, two weeks for a second offense, three weeks for a third offense, and for a month for every additional offense. Since these speed limit laws were implemented in 2001, there has been a great reduction in the speeding problem in the Grand Canal because taxi and cargo boat drivers respond positively to the threat of loosing their boat license.[25]

Other effective forms of wake prevention are the use of license plates and lagoon traffic restrictions. All boats that travel within the Venetian lagoon are required register for a license. Forcing boats to display license plates shows law enforcers that a boat is authorized to be in the lagoon as well as identify boats that are speeding. Those who visit the lagoon can apply for a temporary license. Certain fragile sections of the lagoon have been closed to all large boats. These areas are especially sensitive and cannot withstand the force of the wakes that large boats produce. Those who disobey these restrictions receive the same penalties as those who speed.

2.2.3.2 Restoration Methods [26]

The Venetian company Insula is currently the company contracted to restore these damaged canal walls. The following are the methods of restoration currently in use:

[24] Pax in Aqua: http://www.provincia.venezia.it/paxinaqua/home.html June 2002
[25] Paolo Lanopoppi, President of Pax In Aqua
[26] Insula: http://www.insula.it

- Wooden piles are driven into the bottom along the outer edge of the foundation to support a kerb, or continuous metal sheet piling (approx. 2.5 m deep). They are embedded along the outer edge of the foundation to prevent undermining and water stench, reforming the "scarp" (shoe) at the foot of the foundation.

Figure 2-20 A canal undergoing wall repairs

- Mortar is injected into walls to fill gaps to reconstruct its physical continuity by eliminating porosity inside.
- Mortar joints are restored by making injections made to reinforce the surface. Walls are resealed by a technique known as "binder sealing", in order to reconstruct the missing part of the outer face, thus restoring the body of the wall to its former compactness and physical continuity.
- The ground behind the walls is treated by sealing and waterproofing both it and any sewers running through it in order to prevent water from resuming its deteriorating action and to stop the building fabric from being undermined.
- Corrective action, construction, or partial rebuilding, is performed in order to compensate for any swelling that alters alignment or shifts the original geometry.

2.3 Sponsoring and Related Organizations

This project is sponsored by two organizations, *Pax in Aqua* and Consorzio Trasportatori Veneziani Riuniti (CTVR). Both of these organizations have interests that relate to the project team's study of moto ondoso. The Commissario del Governo Delegato al Traffico Aqueo nella Laguna di Venezia is also interested in the reduction of moto ondoso and assisted the team during the project.

Figure 2-21 An Anti-Wake Banner in Venice

2.3.1 Pax in Aqua

Pax in Aqua (Peace in the Water) is an association made up of twenty organizations that joined forces in 1996 to attempt to reduce the amount of wake that exists in the lagoon of Venice. *Pax in Aqua* collects funds to pay for all the programs they sponsor by requiring an annual fee in order to be part of the association. Due to the increase in damage done to the canal walls by boat wake, *Pax in Aqua* has had to increase membership fees almost every year.[27]

In December, 2001, the Italian government declared Venice a national emergency due to the rate of erosion. A Special Commissioner was appointed in attempts to take action against the dangerous state of the canal walls.[28]

Although enforced regulations would help Venice's situation, solving the problem is dependent on the cooperation of its residents. The growing problem of wake damage is made blatantly obvious to everyone in Venice through the visible damage of canal walls and bridges, but residents are still reluctant to take action against the phenomenon. Due to the need for cooperation, one of the main goals of *Pax in Aqua* is to educate the public about the growing problem of wake damage. This is accomplished in collaboration with the commune of Venice, Magistrate of Waters, Harbormaster's office, and the Province of Venice. With the help of these groups, *Pax in Aqua* organizes a variety of initiatives, conferences, and meetings to discuss the phenomenon and proposed methods to slow the damage to the canal walls. *Pax in Aqua* also holds assemblies at the local schools to alert schoolchildren about the current situation and tell them what they can do to preserve the lagoon.

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[27] Pax in Aqua: http://www.provincia.venezia.it/paxinaqua/home.html April 2002
[28] Paolo Lanopoppi, Head of *Pax In Aqua*

2.3.2 Consorzio Trasportatori Veneziani Riuniti (CTVR)[29]

The Consorzio Trasportatori Veneziani Riuniti (CTVR), formed in 2000, is an organization which operates similarly to a local teamster association. It is composed of a number of small companies, all of whom have the common goal of serving the interests of cargo boat drivers by increasing the efficiency of the Venetian cargo transportation system. Alone, these companies do not have enough of an influence on the current system, but by working together they have the power to make changes that would increase their productivity. Currently, CTVR boats make up 70% of the total number of cargo boats traveling in the canals.

Figure 2-22 A Well stocked CTVR Cargo Boat

2.3.3 Commissario del Governo Delegato al Traffico Aqueo nella Laguna di Venezia

On 15 November 2001, the Mayor of Venice appointed a special commissioner to oversee the boats of the Venetian lagoon. This commissioner has the power to override all the local aquatic authorities, which solved the problem of overlapping jurisdictions between Venice's 7 policing forces, as well as the local harbor masters. The creation of this position also created an official delegate for the study of moto ondoso. This new position, dedicated totally to the reduction of moto ondoso has created new speed regulations that are consistent for the entire lagoon, increased the severity of and enforcement of speed limit violations, and conducted studies on the reduction of moto ondoso. By showing that the enforcement of speed limits would help reduce the amount of wake and destruction to the canal walls, the organization could use that result as reason to enforce their posted speed limits more strictly.

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[29] Re-Engineering The City OF Venice's Cargo Delivery System, IQP, 2001. pg. 24

2.4 The Controversial Issue of Moto Ondoso

The team met with two organizations with extremely different views on the moto ondoso phenomenon. These two conflicting views gave the team insight into the prominent, constant debate that moto ondoso causes in Venice.

2.4.1 *Pax in Aqua's* View on Moto Ondoso

The team met with the elected head of *Pax in Aqua*, Paolo Lanopoppi. Signore Lanopoppi discussed the importance of decreasing the amount of moto ondoso within the Venetian Lagoon. During the past five years *Pax in Aqua* has fought moto ondoso by increasing public awareness of the problem, conducting studies on boat wakes, and appointing a special commissioner who is able to create regulations that override any existing regulations already set for the lagoon. Those involved in *Pax in Aqua* (5,000 of the 60,000 Venetians) as well as many others believe that moto ondoso is the primary cause of destruction to the canal walls, and unless it is decreased considerably the city of Venice will be in great danger.

2.4.2 Insula's View on Moto Ondoso

The team met with the Director of Technical Operations at Insula, Ivano Turlon. Signore Turlorn does not attribute the damage of canal walls to moto ondoso. There are many factors that add to the damage, and there is no way to tell how much, if any of that damage is attributable to the wakes of boats. Some of these factors include underwater turbulence, sediment levels, canal width, depth, state of repair, natural weathering and decay, and physical collisions between boats and the canal walls. Signore Turlon also insists that design and construction materials of the canal walls are reasons for their rapid destruction. Insula has a method of constructing and reinforcing canal walls that would make them much more durable and resistant to erosion. This method of canal wall construction uses a slanted wall rather than a vertical wall, and uses more concrete that the traditional walls. Although a more modern canal wall construction would help preserve the city structurally, it would also ruin the aesthetic value of the city's appearance and therefore people are resistant to this change. They want to preserve the authenticity of the city by maintaining the original construction of the canal walls, even though this method is not practical anymore.

The lifestyle of Venetians has changed, and they now use large boats that create lots of turbulence and motion in the water. The original walls were not designed to withstand this amount of water motion, but the more modernized version of wall construction is designed to accommodate the advances that Venice has encountered through out the years. According to Signore Turlon, if changes were made in the construction of the walls, moto ondoso would not cause a problem or create a threat to the city.

3 Methodology

The ultimate goal of this project was to create a system of assessing canal wall damage caused by boat traffic and to use this system to determine the effect of changes in traffic patterns. The analysis of the collected data showed the City of Venice the effect of reducing canal traffic of different boat types, enforcing speed limits, and other possible scenarios. One application of this analysis will allow the city to asses the benefit of the reduction of cargo boat traffic as, proposed in the project that describes the re-engineering of cargo delivery system via a central cargo warehouse.

The main objectives were to:

1. Measure the wakes produced by various types of boats
2. Calculate the total energy released by boats into the canal system
3. Create a system of assessing how much energy is released into each canal segment
4. Determine the impact of variations in traffic flow

The following sections describe the methodology the project team followed to fulfill the objectives.

- **Section 3.1** describes the geographical area covered by the study and the path by which the team met its goal.
- **Section 3.2** covers the methodology used to measure the wake of various types of boats.
- **Section 3.3** discusses the method the project team used to calculate the amount of energy that came from the measured boat wake and how the energy values will be used in the team's analysis
- **Section 3.4** explains the system the team developed in order to assess the amount of energy that is released into each canal segment
- **Section 3.5** discusses how the team analyzed the collected data

The following flow chart shown in Figure 3-1 outlines the methodological portion of the project. The flow chart describes the data collected by the team and how it was used to create an index in conjunction with previously collected and expanded traffic data. The portion of the chart on the right shows the types of data we collected and the steps we went through to calculate energy values with this data. The left portion of the chart depicts the process we used to produce useable traffic data. The final result of the process is a total Moto Ondoso Index.

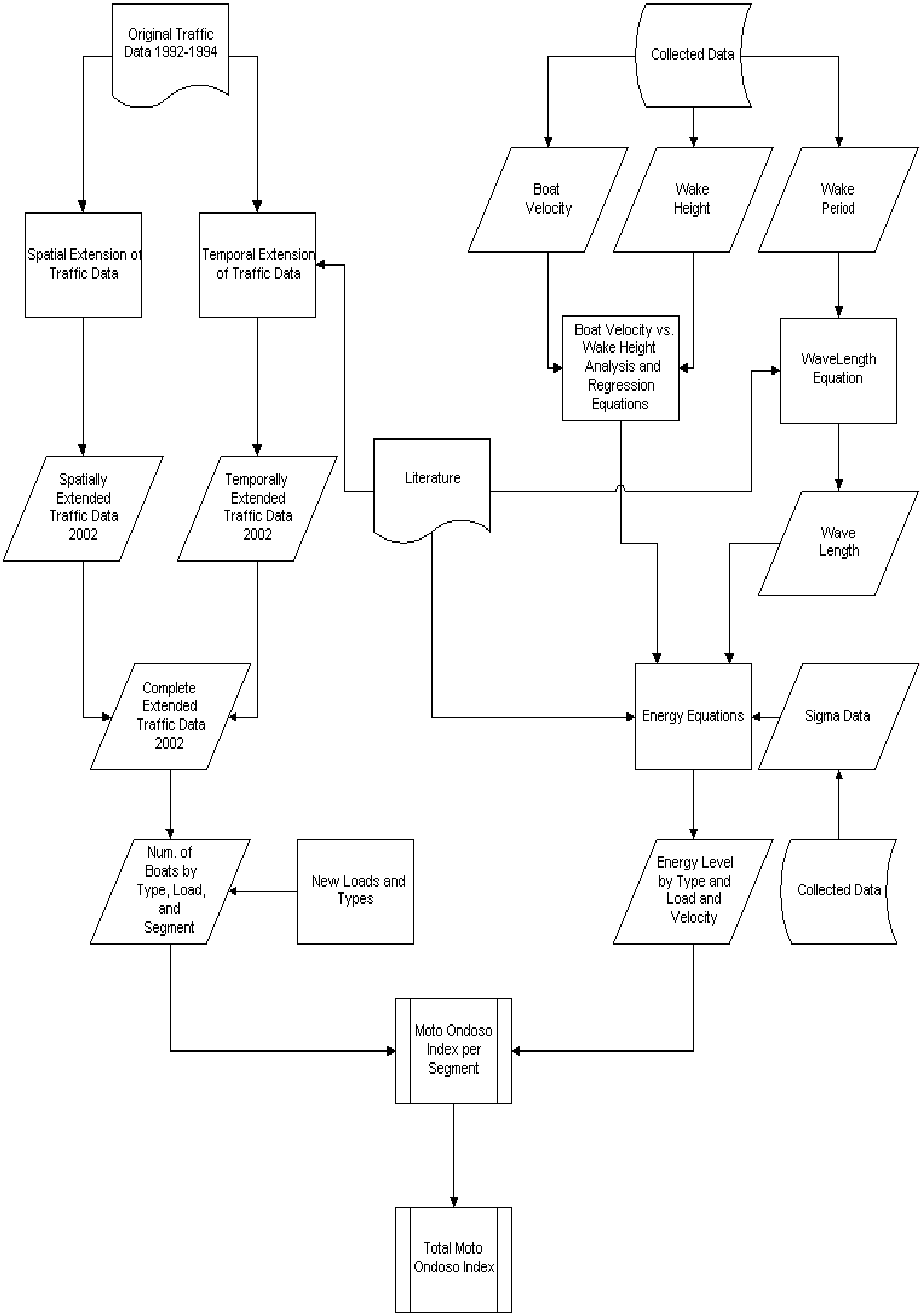


Figure 3-1: Methodology Flowchart

3.1 Area of Study

During the month of June 2002, the team collected data in a group of canals throughout the city that met specific requirements. To begin the selection process, the team obtained a map of Venice and marked areas that were possible data collection sites. Each site was then visited in order to determine its usability. Useable canals had the following qualities:

1. Existing and recent data on traffic flow, canal width, and canal depth.
2. Accessible to the data collectors by bridge or fondamente.
3. A straight segment between 10 to 30 meters long on which to measure speed.
4. Moderate traffic flow.

Sites used by the team are shown in Figure 3-2. Appendix G contains pictures and lists the site specific specifications for each data collection site.

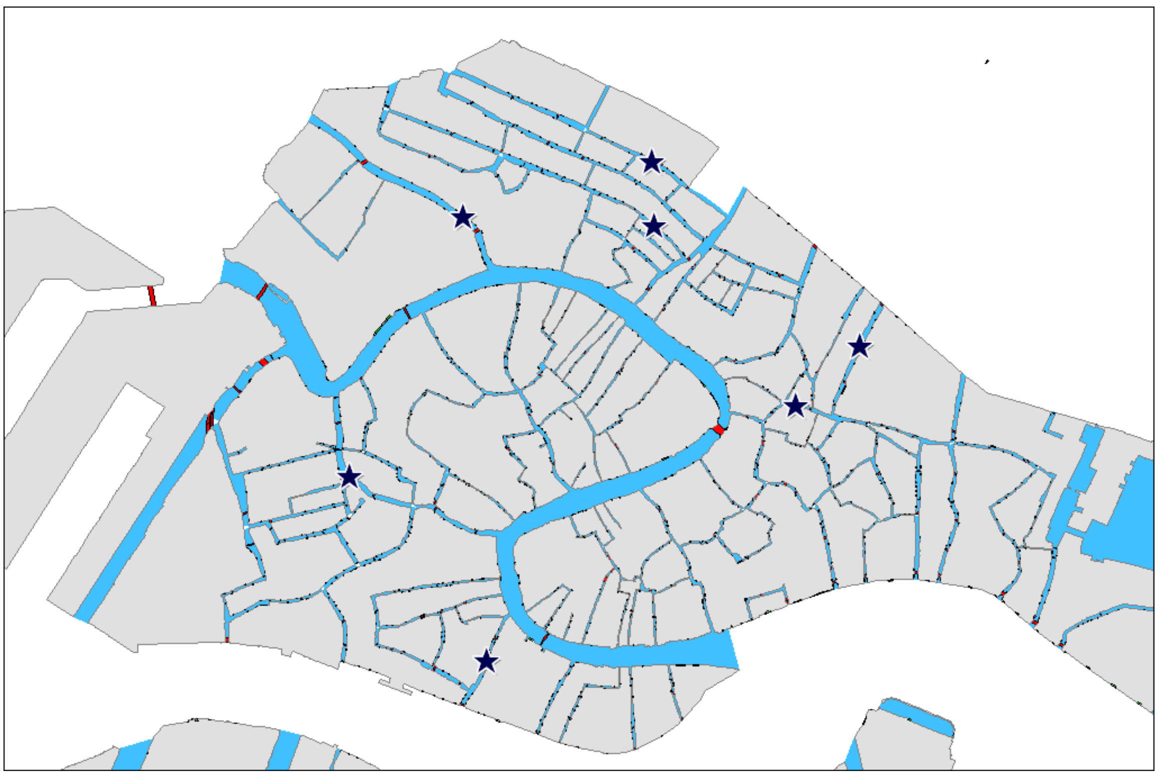


Figure 3-2 Data Collection Locations around the Historical Center

The traffic data[30] enabled the team to make yearly estimates of the amount of energy released by each boat type per year. The existence of fondamente at the collection sites helped with ensuring accuracy for measuring wake height. Since motorboats change speeds and gears, i.e. drive

[30] Carrera, Fabio; Il Traffico Acqueo Nei Canali Interni Di Venezia, 10, Luglio, 1996.

and reverse while going around turns and bends in the canals, the selected sites had to have a straight segment of between 10 and 30 meters in length.

The data collection sites exclude canals where traffic flow is extremely high because the wakes caused by the high traffic flow would affect the accuracy and precision of the data. The data collected was later used to make an estimation encompassing all of the Historical Center of Venice. The site chosen for data collection on a given day was based on traffic flow of the different canals as well as convenience. All boat types and canal widths listed in existing traffic data were covered during the data collection period. The particular site for a given day was chosen using the traffic flow data to determine which types of boats will most likely pass through the canal and at what time.

An example of a canal the team found useable was the Rio della Miseracordia. All listed criteria were met by this canal: traffic data existed on this canal; a fondamente and a bridge were present to make data collection possible, there existed an straight away in excess of 50m (a distance of 30.6 m was used by the team at this location), and the traffic flow was not overbearing making accurate data collection possible. Rio della Misericordia and the boats that traveled through it during data collection times will be used as an example throughout the rest of the methodology.

3.2 Measurement of wakes produced by various boat types

Before starting data collection, the project team obtained a boat guide from Worcester Polytechnic Institute's Venice Project Center (VPC). The boat guide included all of the major boat types that travel the inner canals of Venice. The boats were organized into 18 different types, which were further divided into 18 subtypes, which reflected the different shapes of hulls of each boat type. This information helped us understand different boat types and also made the identification and sorting processes easier and more efficient.

Once a site was selected, certain steps were taken to prepare it for the data collection process. First, a straight of the canal was chosen, measured with a measuring tape, and marked with chalk. This segment was used as the time trial track, which allowed the team to later calculate speed of the boat from this previously measured distance and time it took for a boat to cross it. The distance measured was noted on the data sheet by the data-recorder, person 1 (Number 1 in Figure 3-3). Person 1 stood at one end of the measured distance, and person 2 (Number 2 in Figure 3-3) stood at the other end. Person 3 (Number 3 in Figure 3-3) stood at the edge of the canal, in a location clear of parked boats and other obstructions.

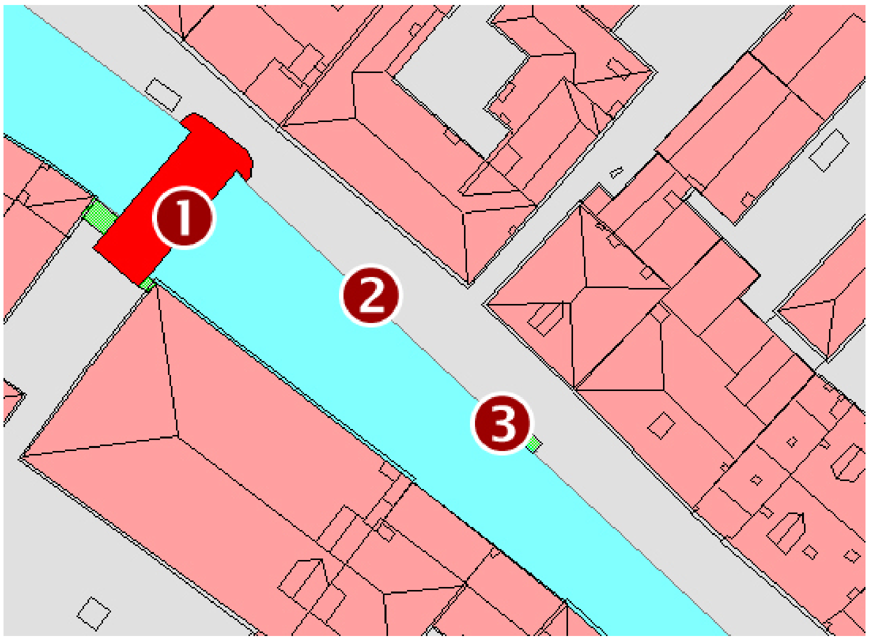


Figure 3-3 Sample Locations for Each Team Member

The three main objectives to the data collection process were to:

1. Determine the speed of boats passing through canals selected for data collection
2. Measure the amplitude of the wake produced by these boats
3. Determine the wavelength of the produced wake through wave period measurements

Persons 1 and 2 collected the data needed to determine the speed of the passing boat. Persons 1 and 2 were equipped with stopwatches to clock the boat as it traveled the measured distance, and two-way radios with which they relayed information. Take for example a small cargo boat that approached the measured distance on the Rio della Misericordia from person 1's side. Person 1 alerted person 2 via two-way radio of the approaching boat by boat type. The boat type was identified as a small cargo boat (one of the categories in the boat guide provided by the VPC). Person 1 then gave person 2 a signal via radio when it was time to start the stopwatch. The timer was started when the boat's bow crossed the start of the measured distance and stopped when the bow crossed the end of the measured distance. Person 2 then relayed the reading of 13 seconds on the stopwatch back to person 1. Person 1 recorded this time on the data collection sheet and the process would be repeated for the next approaching boat. If a boat were to approach the data collection site from the opposite side, person 2 would begin the stopwatch when the boat entered the measured distance, and person 1 would alert them to stop the stopwatch when the boat exited. The data collection process is illustrated in Figure 3-4.

In order to determine the speed of each boat in kilometers per hour, the speed in meters per second was first determined. The calculation was made by dividing the length of the measured distance by the time a boat took to travel the distance. In the case of the mentioned cargo boat, the speed in meters per second was 2.35 m/s (8.46 km/h).

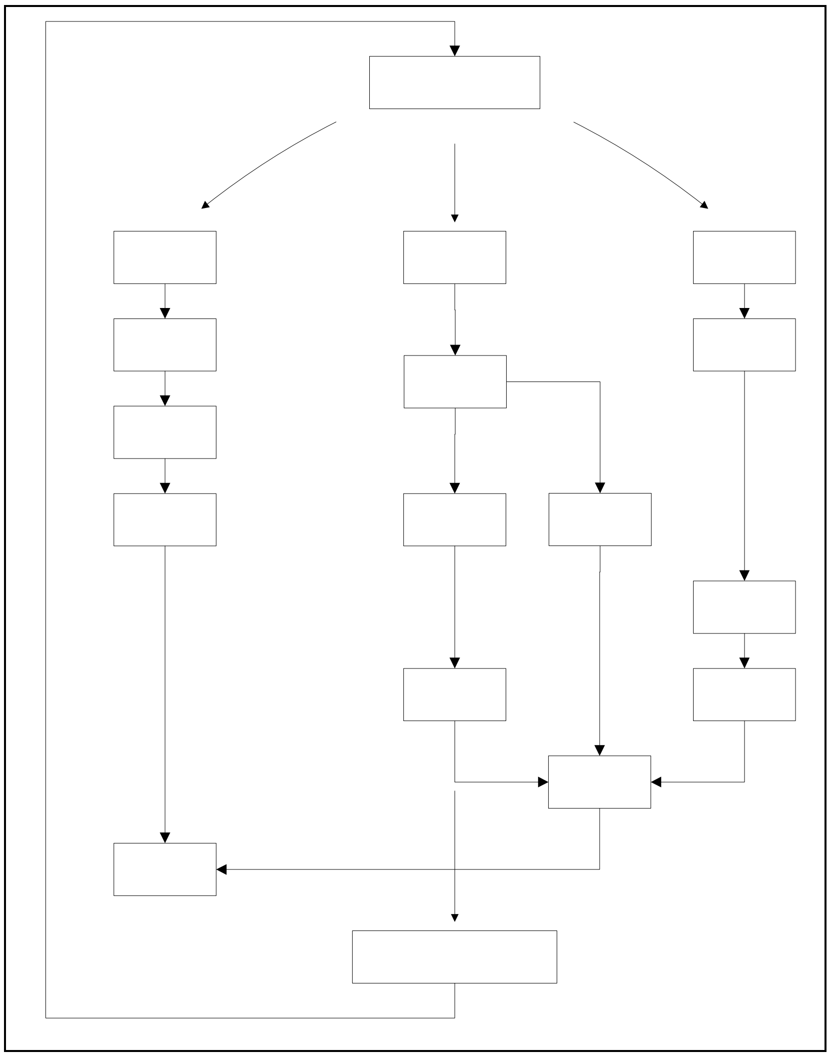


Figure 3-4 Flow Chart for Data Collection

The size of the wake produced by passing boats was measured by person 3. The wake measuring device used to determine the height of the wake was a length of measuring tape (units in centimeters) attached to a long black stick, shown in Figure 3-5. To prepare the device for wake height measurement, the

Figure 3-5: Wake Measuring Stick

stick was wet in the canal and then coated with a thin layer of flour. To measure the wake height, the end of the stick was first placed at the surface of the water as a boat approached. As the wake came into contact with the canal wall it would wash a length of the flour coating off the stick. This process is illustrated in Figure 3-6. The clean length of stick was then visually inspected and recorded as the

Figure 3-6: The wake measuring device before and after measuring a boat's wake

half-amplitude of the wake. The half-amplitude of the small cargo boat in Rio della Misericordia was measured to be ten centimeters and the measurement was radioed to person 1 to be recorded.

Wavelength, or the length of one cycle of a wave, is illustrated in Figure 3-7. In this experiment, wavelength is dependant on the wave's period, which is the amount of time a wave takes to complete one cycle. The period was measured by person 2 in addition to speed and was measured by selecting a fixed visual point on the canal wall and timing with a stopwatch how long the wave's peaks would pass a location along the canal wall. Since person 2 was already using one stopwatch for speed measurements, a second stopwatch was necessary for period measurements. This data was then radioed to person 1 and recorded. Time of day, approximate payload and any other observations were also noted on the data collection form by person 1.

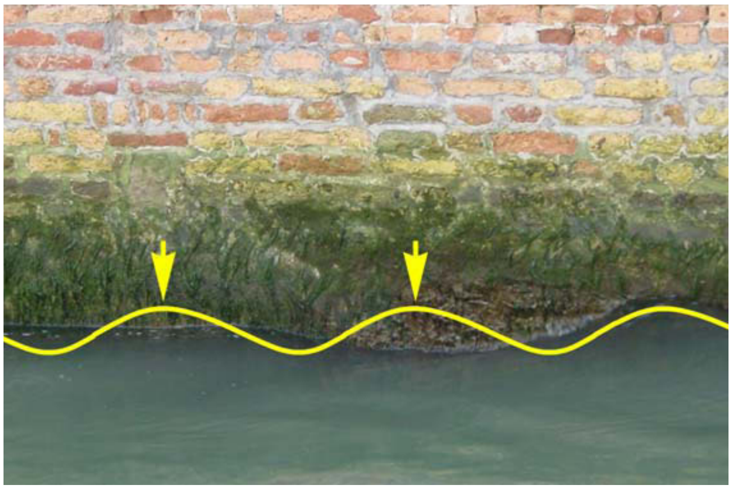


Figure 3-7: The two arrows in the figure above show the beginning and end of one wavelength

The collected data was entered and stored in a table within a database that encompasses all aspects of the project.

3.3 Calculation of Total Energy released into Canals by Wake

As previously mentioned in the Background chapter, Section 2.2.1.2), Energy of Boat Wakes, the team used the following equation to determine first the energy released into the inner canals by individual boats:

$$E = \frac{1}{8}\gamma H^2 L \sin\sigma \quad \text{Equation 1}$$

To calculate the wavelength, *L*, the team used the following equation which includes the period of the wake, *T* (the calculation of period was described in Section 1.2):

$$L = \frac{gT^2}{2\pi} = 1.56T^2 \quad \text{Equation 2}$$

The cargo boat discussed in section 1.2 produced a wake with a period of 0.91 seconds. Therefore, by plugging this value into the stated equation, the team obtained the following value for wavelength:

$$L = 1.56 \times 0.91^2 = 1.29 \text{ m}$$ Equation 3

Then the project team used this value of wavelength and amplitude of 0.2 m to calculate the energy of the small cargo boat:

$$\frac{1}{8} \times 1 \times 0.2^2 \times 1.2918 = .0064 \text{ kg-m}$$ Equation 4

After calculating the energy of each individual boat, the team sorted the results by boat type and took an average of each boat type. Then, using existing traffic data for the canals, which includes the number of passes each boat type makes in a day and an hour, the team determined the amount of energy that each boat type was responsible for releasing into the canals. By again using the traffic data, a value for the total energy released into the canal system was calculated.

3.3.1 Measuring Sigma (σ)

Values for the angle sigma, σ in the energy equation were determined in a study completed in 1996[31] using electronic sensors. Values were said to vary slightly in the study, but a standard value of 34.5 degrees was used in the calculations for the study. Since the energy calculations are sensitive to the value of σ, the team had to take some measurements to decide if this standard value for σ could accurately be used. The team selected criteria they believed might have an impact on the size of σ. These criteria included approximate payload, speed, and boat width.

[31] Personal correspondence with Sergio Vazzoler, author of "Moto Ondodo Nei Canali Di Venezia", July, 2002. And, Vazzoler, Sergio and Canestrelli, Paolo, "Moto Ondoso Nei Canali Di Venezia" ATTI: Classe Di Scenze, Fisiche Matematiche E Naturali; Instituto Veneto Di Scienze, Lettere Ed Arti; 1996

The team selected Rio di Noale as the site where angle data would be collected. This canal was ideal for a few reasons. The canal was wide enough so that there was ample space for wake to travel away from the boat before impacting and reflecting off of the canal walls and there was a bridge spanning it from which pictures of boat wake could be taken. As boats passed under the bridge we took pictures of the end of the boat and its wake and recorded the boats approximate payload, speed and boat width. Payload was visually estimated and recorded under three categories; low, medium, and high. Speed was not measured in the same manner as during data collection of wake measurements, as only approximate speeds sufficed for the purposes of this data collection procedure. Speeds were recorded as slow, medium, and fast. Approximate boat width was recorded as small, medium, and wide. In order to measure σ, a protractor was used against the pictures of the boat wake. Using the protractor, we measured the angle the wake made with the line normal to the back of the boat. Figure 3-8 shows an example of the angle that was measured. From initial inspection, the values of σ did not vary more than one degree from each other. None of the criteria the team believed might affect the size of the angle had a noticeable impact. The team was therefore able to use the standard angle of 34.5 degrees in energy calculations.

Figure 3-8: The σ Angle

3.4 Calculating the Moto Ondoso Index

After energy values were calculated for each boat type at various speeds, the team examined the energy expelled from boats of each boat type traveling at various speeds including the current speed limit[32] of the inner canals, 5 kilometers per hour. This was done by making a database of the amount of energy released by different boats with varying payloads (low, medium, high) at various speeds. The hour was also taken into account to see how energy levels in the canals varied throughout the day. First, regression curves were made of velocity vs. energy plots for each boat type at the three different payloads. The team chose the following speeds at which to find released

[32] Current speed limit in the inner canals of Venice at time of this publication was 5 kilometers per hour, 04.07.2002

energy: 4, 5, 6, 7, 11, and 20 km/h. These speeds gave a variety of measurements that included the speed limits that the team could work with to analyze later. To find the amount of energy released by each boat type at each speed, the team plugged in the velocity values into the regression curve equations and the resulting energy values for each boat type were entered into the database. Table 3-1 shows a sampling of this database. The full database can be found in Appendix C.

Boat Type Name	Payload	Energy at 4kmph	Energy at 5kmph	Energy at 6kmph	Energy at 7kmph	Energy at 11kmph	Energy at 20kmph	Average Velocity (km/h)	Energy at Avg Velocity
Large Cargo Boat	Low	1.36	1.84	2.36	2.91	5.40	13.49	13.39	7.05
Large Cargo Boat	Meduim	1.66	2.27	2.94	3.65	9.89	16.01	8.62	4.89
Large Cargo Boat	High	0.33	0.62	1.02	1.56	5.44	10.34	10.06	4.25
Small Cargo Boat	Low	0.13	0.36	0.80	1.57	11.47	23.92	12.84	22.69
Small Cargo Boat	High	0.13	0.36	0.80	1.57	11.47	23.92	21.27	23.92
Taxi	Low	1.15	1.68	2.28	2.97	6.39	7.77	10.30	5.72
Taxi	Medium	0.33	0.69	1.28	2.14	9.69	14.55	14.52	14.85
Taxi	High	0.33	0.69	1.28	2.14	9.69	14.55	10.63	8.62
Personal Boat senza Cabin	Low	0.78	1.23	1.78	2.43	6.11	11.00	13.11	8.73
Personal Boat senza Cabin	Medium	1.47	2.10	2.82	3.62	7.50	9.48	11.41	7.96
Personal Boat senza Cabin	High	6.40	7.82	9.22	10.60	15.93	27.31	9.48	13.93

Table 3-1 Energy of Different Boat Types at Different Speeds in kg-m

To obtain index values from this point, we applied previously collected traffic data. The traffic data available, however, was very old (1992-1994) and did not cover the entire city. Before index values could be calculated, the traffic data was expanded spatially to cover the entire historical center, and temporally so that a traffic database that was representative of boat traffic in 2002 could be used.

3.4.1 Spatial Extension

Previously collected traffic data covered certain highly traveled canal segments in the city. In order to have a more accurate representation of spatial coverage, the data had to be extended past just a segment. Segments to which data could be extended to had to have a segment immediately adjacent to it. Information regarding adjoining segments, one way canals, closed canals, and rio terras (filled in canals) was taken into account before an extension was made for a particular segment. For example, Rio della Miseracordia is divided into six segments; MISE1 to MISE6. Traffic data existed for MISE1, so to extend that data to MISE2, a map was used to check for adjacent canals that could feed or remove traffic from that segment. A certain percentage of MISE1's traffic was decided to exist in MISE2, and in this particular case there were no cases of traffic injection or reduction by adjacent canals, so we extended 100% of the data of MISE2 to MISE3 and MISE4. The rest of the old traffic data was extended in a similar fashion, always taking into account adjacent canals that could add or remove traffic. Segments to which accurate extension predictions could not be made were not included in the spatial extension. An example of a canal that was not fully extended was the Grand Canal. The segments on which traffic data was collected on the Grand Canal seem relatively close on a map, however, the number of turn-offs and adjacent canals between segments adds and subtracts so much traffic that an accurate extension percentage could not be made. The Giudecca Canal was another canal not extended for the same reasons. In Figure 3-10, the canals segments shown in orange are the segments with original and expanded traffic data and are therefore the canals included in the index calculations.

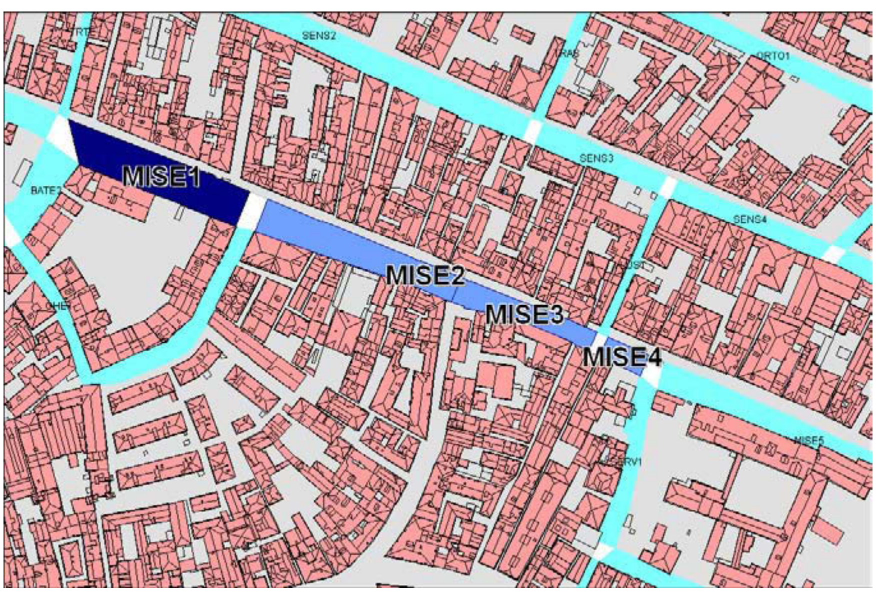


Figure 3-9 Sections of Misericordia That Data Was Extended To

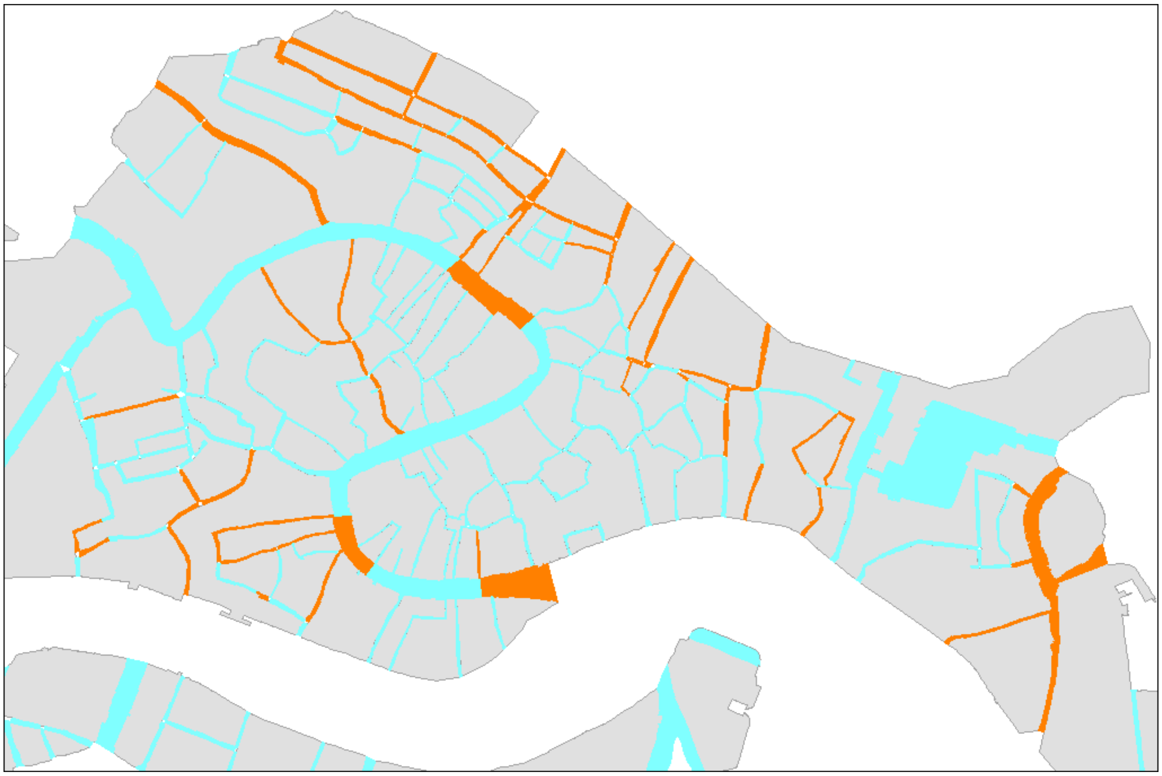


Figure 3-10 Canal Segments Included in Original and Expanded Traffic Data

3.4.2 Temporal Extension

The population of motorboats in Venice has grown since traffic data had been collected last. According to Venezia la Cotta dei Rii[33], Venetian canal traffic has increased an average of 2.5% ever year since 1994. This means that Venetian traffic is now 28% higher than it was in 1994. Before temporal extension of the traffic data could occur, traffic fluctuations by season were taken into account. Lagoon traffic generally differs between the summer and winter months; a direct influence by the tourist population in the city and weather conditions. Summer is defined as May to September, and winter as October to April. An example of the variation

Boat Type	Winter/Summer
Cargo	57/70
Taxi	34/39
Personal	11/79

Table 3-2: Winter/Summer Ratios for Boat Traffic

[33] Caniato, Giovanni; Carrera, Fabio; Giannatti, Vicenzo; Pypert, Philippe: Venezia la Cotta Dei Rii, 1999.

between the two seasons is the personal boat population. For every 11 personal boats navigating the canals in the winter months, there are 79 in the summer. Differences in population between seasons were noticeable for all boat types and were accounted for using their traffic data. Ratios were developed using the previously mentioned report to convert winter traffic data for each boat type to summer data, and vice versa. Table 3-2 shows the ratios used for cargo, taxi, and personal boats. With the application of these steps, traffic data was extended to the current day.

3.5 Determine Impact of Variations in Traffic Flow

To analyze the impact on Venice if there were to be a change in traffic flow the project team used the energy regression equations to calculate Moto Ondoso indices of different traffic scenarios. The team examined the resulting data in the following ways:

1. Determined how the speed of canal traffic affects energy levels.
2. Made projections of how severely increased/decreased traffic flow of different boat types would affect the amount of energy released.
3. Estimated the cost of benefit of the proposed cargo warehouse.

First the team used the collected data to create graphs showing how the different variables of boat traffic affect the energy released by the boat. These graphs showed which variables, if changed would affect wake size the most and gave us insight into which changes in traffic flow would effectively reduce energy. For example, if wake size increases exponentially with speed, enforcing speed limits would greatly reduce wall damage. If payload on the other hand does not have a dramatic effect on the size of wake, changing the weights of boats would not greatly affect the energy they release. Graphs were made showing speed, payload and boat type vs. energy released.

Since wake size and energy are also dependent on boat speed, the energy in the canals will change with the speed of the boat. Projections were made of how total energy would change if all boats were to slow down or speed up.

The WPI project "Re-engineering of the Cargo Transportation System" proposed a central cargo warehouse that would reduce cargo boat traffic by 90%. Using the calculated indices for cargo boats and the cargo boat traffic data, the team made projections on how the total energy in the canal system as well as specific canals would change if the warehouse were implemented.

4 Results

The following chapter presents the data collected by the project team during June and July, 2002. The data presented represents what is most important to the team's analysis which is presented in Chapter 5. Results on boat speed, wake height, payload, and energy are discussed in this chapter. The speed at which boats travel in the canals has a direct impact on the size of wake they produce. The amount of payload carried by boats also plays a part in the size of a boat's wake. Wake height in turn directly influences the amount of energy that impacts the canal walls from boat wake. Other factors that have an effect on energy values are the wave period, and the angle at the waves make with the wall on impact. These factors are also discussed in this chapter. The results of energy calculations that are presented show the boat type(s) that are responsible for the most energy released into the canals per passage.

4.1 Boat Speed

The team calculated the speed of each boat passage that was recorded during data collection. This speed data was needed for later analysis and extrapolation of energy values from regressed equations. The average speed traveled by boats we studied was found to be 12.5 km/h; over 7 km/h over the posted speed limit for the inner canals of 5 km/h. The average speed of each boat type was also calculated to determine which types disobeyed the speed limits and by how much. Figure 4-1

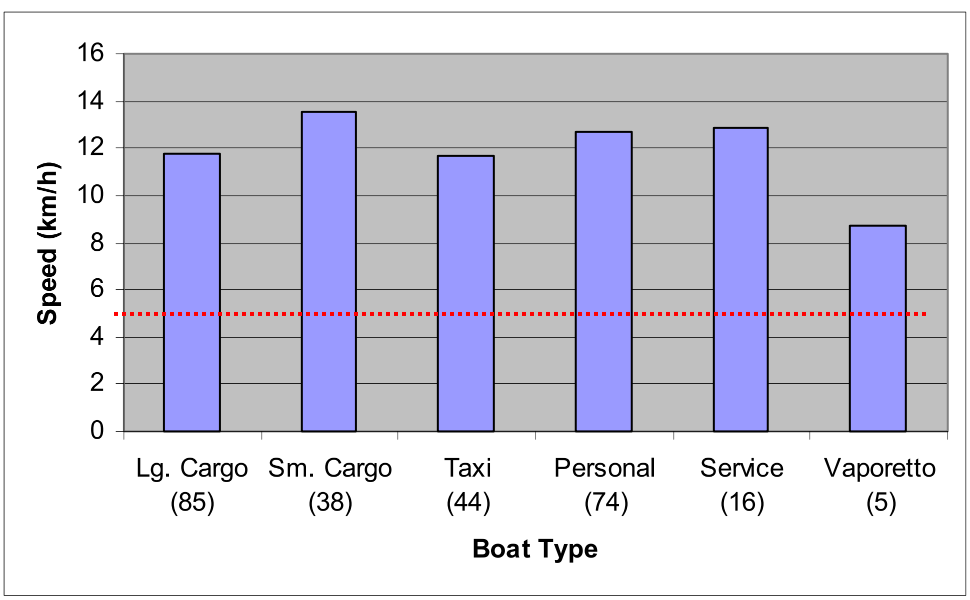


Figure 4-1 Average Speed of Different Boat Types In the Canals of Venice
(Dashed line indicates current speed limit)

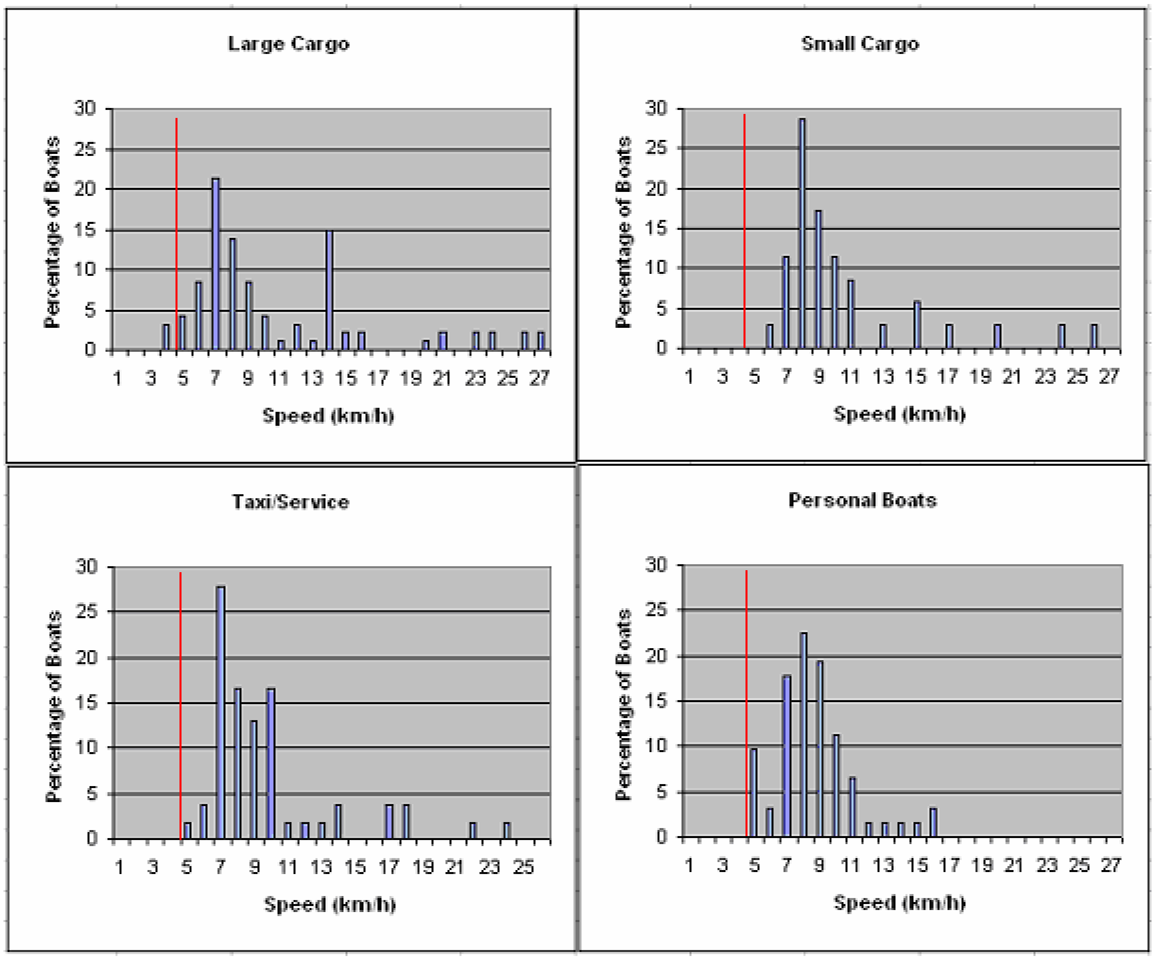
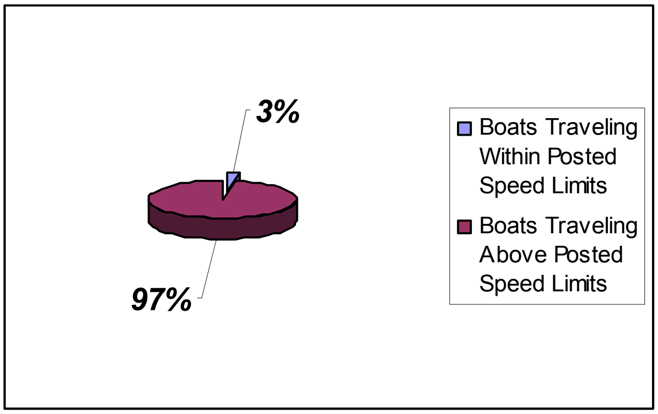


Figure 4-2 Percentage of Boats Traveling at Different Speeds
(Speed limit shown by vertical red line)

shows the average speeds of the boat types on which data was collected and states the number of boats included in this average. Small cargo boats traveled the fastest with an average speed of 13.5 km/h, followed closely by service and personal boats with speeds of 12.1 km/h and 12.7 km/h respectively. The boat type with the slowest average speed was the vaparetto, which traveled at an average of 8.9 km/h. This data was examined more closely to determine the speed ranges at which the majority of boats were traveling. Figure 4-2 shows what percentages of boats are traveling at different speeds. For all boat types, the majority of boats are traveling between 5 and 10 km/h, with the most boats traveling at 7 or 8 km/h. Boats are consistently traveling at speeds above 10 km/h, but very few are traveling at or below the posted speed limit of 5 km/h.

We then calculated the percentage of boats traffic as a whole that travel above the speed limits. Figure 4-3 shows that of the boats on which data were collected, only 3 percent obey the speed limits. Every record we had of boats traveling within the speed limit was a large cargo boat;

therefore 100% of boat traffic of other types was speeding. The percentage of boats that travel within 2 km/h of the speed limit was also determined to see how many boats traveled within a negotiable range. Of the collected data, 13 percent of the boats traveled within 2 km/h of the speed limit as shown also in Figure 4-3.



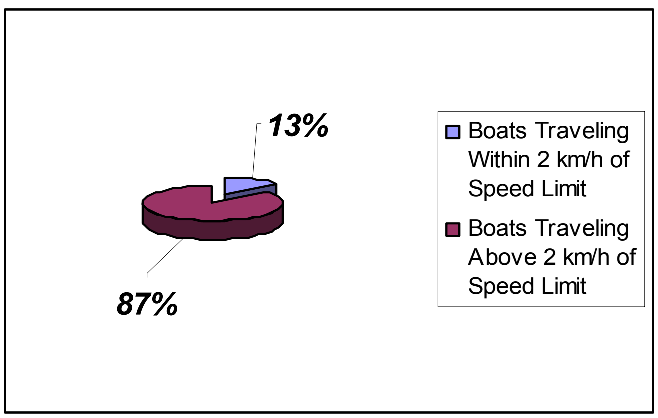


Figure 4-3: Percentage of Boats Traveling At or Within 2 km/h of Speed Limit

4.2 Wake Height

The size of the wake produced by each boat type was very important to this study because amplitude (twice the height of the wake) a key variable in the energy equation presented in section 2.2.1.2 Wake height data can be found in Appendix B. The effects of speed and payload on wake height are presented in this discussion.

4.2.1 Effect of Speed on Wake Height

In a previously completed study, it was found that the height or size of a boat's wake increased with speed.[34] To determine if the result of study was similar to this one, plots were made of wake height in centimeters versus speed in km/h. shows the wake heights of four different boat types traveling at different speeds (the speed limit is indicated by the red dashed line). The four types shown in the plots are small and large cargo boats, personal boats, and taxi and other service boats. All boat types follow the same general trend; wake height increases at an exponential rate as speed increases until the speed of 14 km/h where the rate of wake height increase slows and follows a linear trend. These figures also provide a marker at the speed limit of 5 km/h. This marker shows, in addition to Figure 4-3 that barely any boats in our study follow the speed limits.

As discussed in the previous section, the majority of the boats we studied traveled between the speeds of 5 and 10 km/h. Figure 4-5 shows the average wake heights of each boat type traveling in this speed range. Small cargo boats were shown to create the largest wake of all the boat types. A possible explanation for the comparatively large wakes produced by these boats regardless of speed is the motor of the boat. Small cargo boats have outboard motors mounted at the rear of the boat. When the propeller begins to turn on an outboard motor, it pushes the motor towards the boat, causing the boat to move forward. This action causes pulls the stern of the boat into the water and causes the bow to rise. Inboard motors, as found on largo cargo, taxi, and service boats are located closer to the center of the boat, so do not produce this effect. Personal boats also have outboard motors, but since they are in general much smaller than cargo boats, their

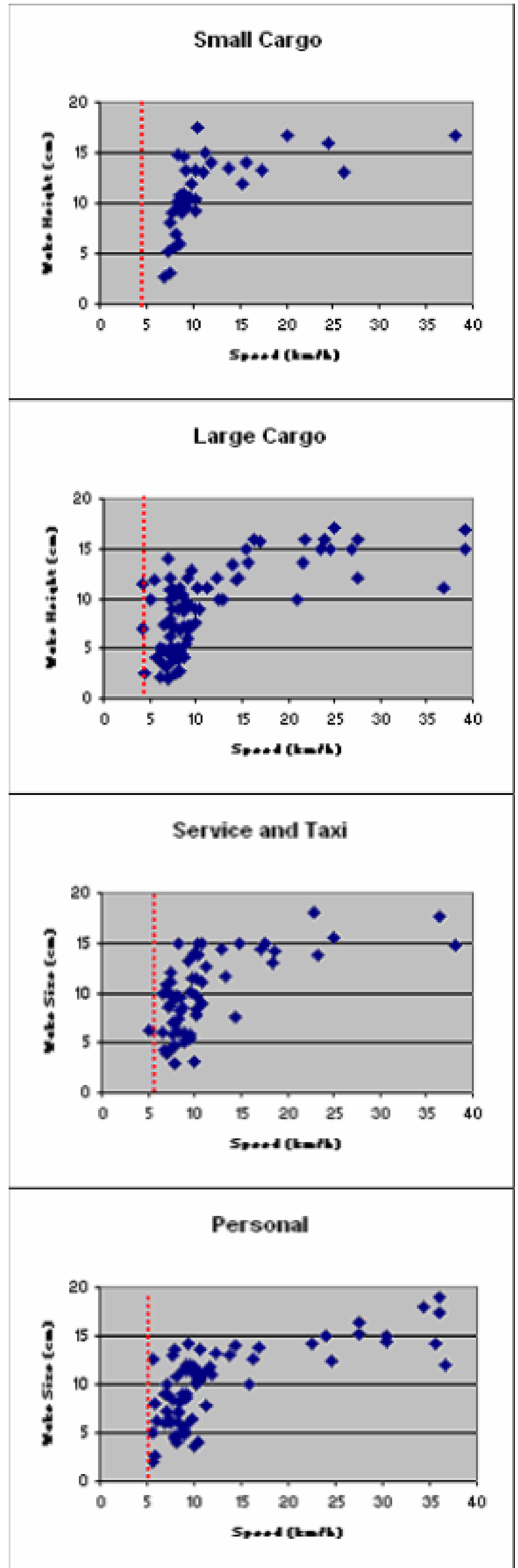


Figure 4-4 Speed vs. Wake Height for Different Boat Types

[34] Comune di Venezia; "Assessorato ai Trasporti e Servizi Pubblici Commissione per lo Studio del Moto Ondoso

motor does not need to be as powerful so the wakes they produce are still relatively small.

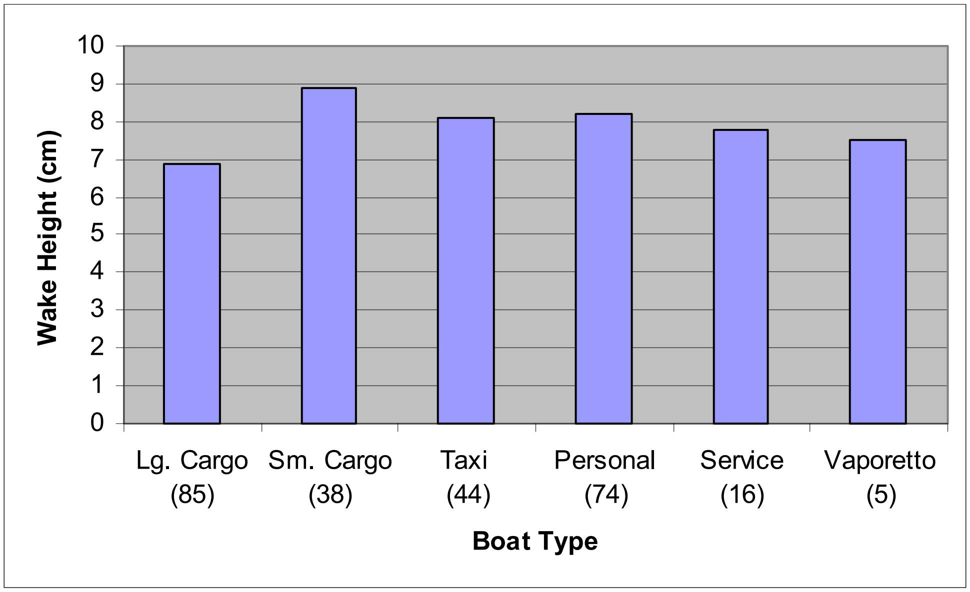


Figure 4-5 Average Wake Sizes of Different Boat Types Traveling Between 5 km/hr and 10 km/h (Sample size is in parentheses)

Speed versus wake height data for all boat types was broken down into two sections: wake heights for speeds below 14 km/h, where the data follows an exponential trend, and above 14 km/h where the data levels off and follows a linear trend. Regression curves and their equations were determined for each boat type using Microsoft Excel. Figure 4-6 compares the rate of wake height growth of each boat type up through 14 km/h. Table 4-1 lists the regressed equations shown in the

Boat Type	Equation
Small Cargo	$y = .038x^{2.5}$
Large Cargo	$y = 1.54x^{0.7}$
Personal	$y = .95x^{0.99}$
Taxi/Service	$y = 1.12x^{0.93}$

Table 4-1: Regressed Equations for Speed vs. Wake Height by Boat Type

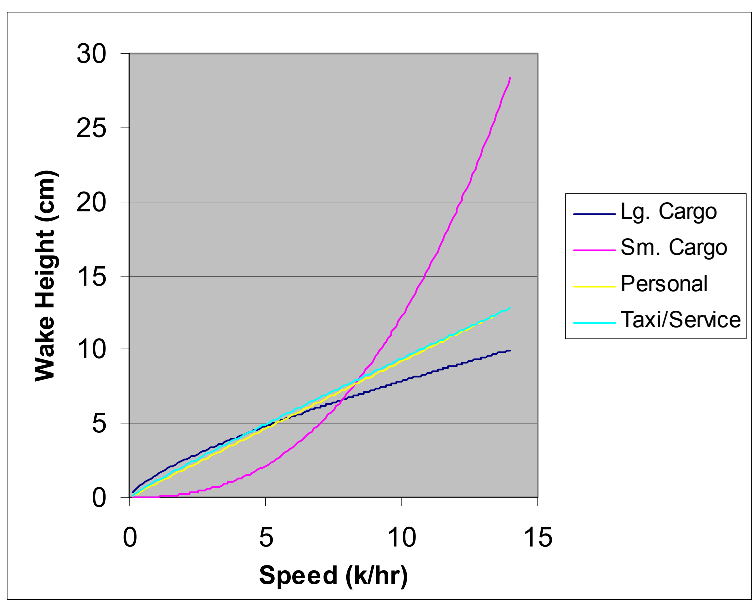


Figure 4-6 Regression Plots of Speed vs. Wake Height for Different Boat Types

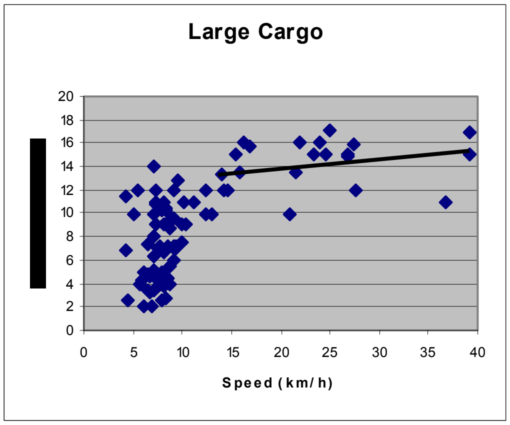


Figure 4-7 Regression of Speed vs. Wake Height for Large Cargo Boats Traveling Above 14 km/h

graph in Figure 4-6. From the plots of the regression curves, it was observed that the rate at which wake size of small cargo boats increased was greater than the rate of increase in the other boat types. This could be due to the fact that they have powerful, outboard motors, as discussed in the previous paragraph. Personal, taxi and service boats show similar trends, and the size of the wake produced by large cargo boats increases at a slower rate than the other boat types as their speed increases. When a boat exceeds 14 km/h, the wake height follows a slowly increasing linear trend. Figure 4-7 shows this trend through the regression line of speed vs. wake height for large cargo boats. At speeds above 14 km/h all boat types follow this increasing trend until the boat reaches planning speed, when the wake size will decrease, as discussed in Section 2.2.1.1 The Venetian canals are too small and narrow for boats to reach planning speed, therefore data showing this decrease in wake height is not visible in these graphs. Regardless of the amount boat speed increases above 14 km/h, wake height will not increase significantly.

4.2.2 Effect of Payload on Wake Height

The collected data was organized into three payload categories; low: 0%-30%; medium: 30%-60%; and high: 60%-100%. The boat type with the most data, and therefore the most payload variation was large cargo boats, so we used this boat type in our examination of payload. Figure 4-8 shows the effect payload has on the wake size of large cargo boats. The team predicted that increasing payload would result in larger wake heights, however upon inspection of these plots, the team realized that wake height did not vary as much as had been originally thought. The average wake size actually decreased as payload increased as shown in Figure 4-9. A possible explanation for this occurrence is the speeds at which boats travel in the inner canals. Cargo boats with a high payload had been observed both in the inner canals as well as in the Giudecca canal where boats can travel much faster than in the inner canals. Payload seemed to make more of a difference at high speeds than at the low speeds in the inner canals. To maintain high speeds, boat propellers must turn fast and hard, which results in large wake. The drivers of the full boats only need to turn the propellers hard to get the boat moving initially, but then rely on the boat's momentum to carry the boat forward at slow speeds. The result would be smaller wake, but increased wash, since the boat would be riding lower in the water.

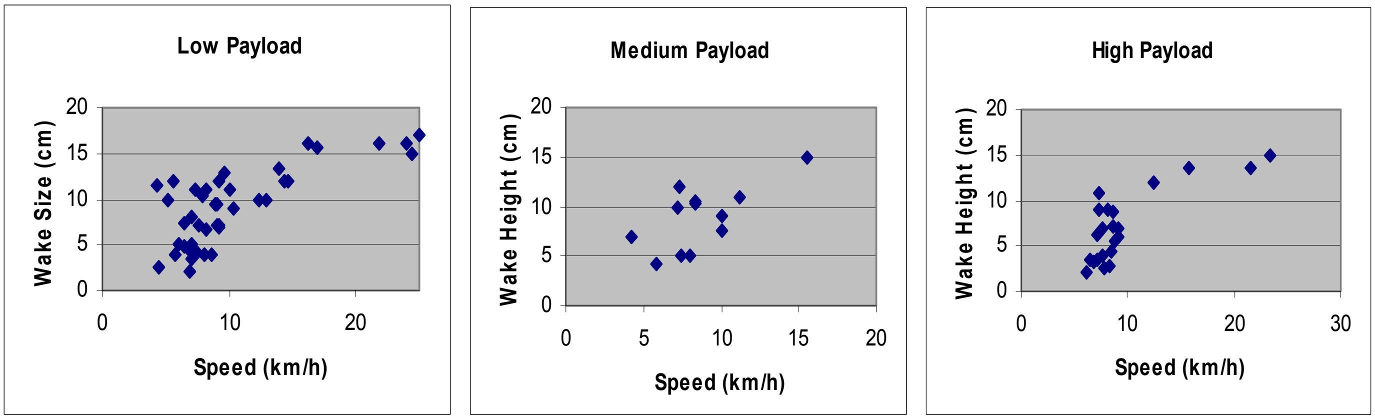


Figure 4-8 Speed vs. Wake size of Large Cargo Boats with Different Payloads

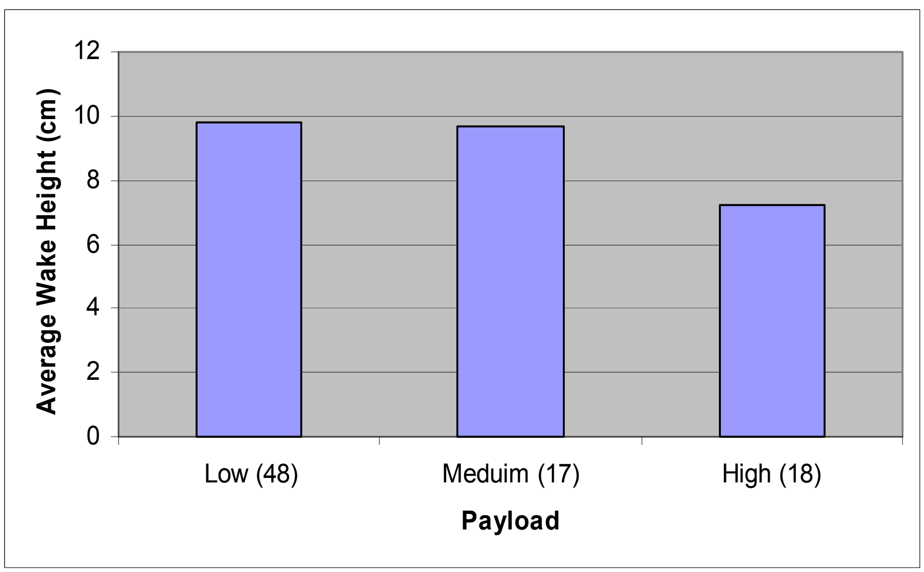


Figure 4-9 Average Wake Size of Large Cargo Boats with Different Payloads
(Sample size is in parentheses)

For this reason the data on small cargo boats was not used as examples for this section. Since wake height decreases with increase in payload if speed is maintained, a sample size with enough variety between low, medium, and high payloads would be needed to effectively demonstrate this trend. Of the 38 records on small cargo boats, 35 of them were at low payload, leaving only three records to describe medium and high payload conditions. It was for this reason that small cargo boats seemed to have unique speed vs. wake height trends; there was not enough medium and high payload data to fully represent the three-payload scenario. Large cargo boats were therefore used as a more complete illustration of trends.

4.3 Wake Periods

As discussed previously in Section 3.3 the wave period is necessary in the calculation of total energy because it is needed to calculate wavelength. After the collection of period data, it was observed that the range of the period of different boats did not vary very greatly (0.85 - 1.35 seconds). From this observation, the team created a table with which they could assign average period values to all boats that data was collected on based on their velocities.

The period of a boat's wake is dependent on the speed the boat is traveling; the faster the boat moves, the shorter the period, therefore, the period value for each boat was determined by its speed. The entire range of speeds was divided into smaller speed ranges, and for each speed range, a unique period value was assigned. These values were selected by averaging the period values found between the limits of the speed range and are therefore representative of an actual period measurement for a boat traveling within that speed range. This method of selecting the period value for a given boat allowed the team to deal with seven, rather than an infinite number of period values, as well as simplifying the data collection process without sacrificing accuracy. The scale developed is shown in Table 4-2.

Boat Speed (km/h)	Period (s)
0 – 1.5	1.35
1.5 – 2	1.3
2.1 – 5	1.25
5.1 – 10	1.1
10.1 – 15	1.0
15.1 – 20	0.95
20.1 +	0.85

Table 4-2 Period Values Used in Energy Calculations

4.4 Boat Hull Observations

The shape of a boats hull affects how it displaces water as it travels. For example, a boat with a long, sleek, streamlined hull moves through the water creating a limited disturbance and reducing the severity of hull wash. A boat with a box-like hull would experience much more drag (i.e. friction) as it moves through the water and would therefore produce a much larger wash. A full range of hull designs were observed during the data collection period. The team's predictions on the effect different shaped hulls were correct; boat types with longer, sleeker hulls produced less disturbance and hull wash while boats with more box-like hulls produced much more disturbance and hull wash. Since wash also creates motion in the water, some erosion can be attributed to hull wash. Since boat wake, rather than wash, is the main focus of this project, its size and effects were not closely observed. However, it was observed that if boats in the inner canals were required to have sleek, streamlined hulls, the amount of hull wash and disturbance could be reduced. Limiting disturbance would lessen the erosive effects of the wash on the canal walls.

4.5 Energy

The amount of energy released by a boat type varies depending on the speed of the boat and the type of boat. Speed is a factor because it is directly related to the size of the wake produced, and wake size directly influences the amount of energy released by the boat. Boat type plays a role because the rate at which wake size increases with speed varies by boat type as previously illustrated in 4.2.1 On average, small cargo boats release the most energy per boat passage (150 kg-m), followed by taxi boats (129.7 kg-m), personal boats (127.8 kg-m), service boats (123.6 kg-m) and large cargo boats (110.4kg-m) respectively. Vaporetti release the least amount of energy per boat passage (105.8 kg-m), as shown in Figure 4-10.

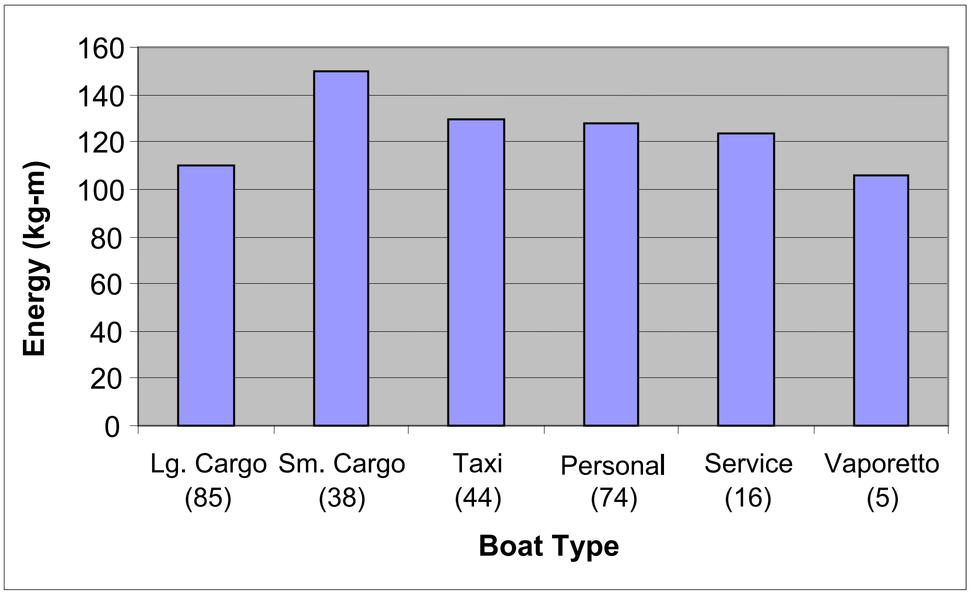


Figure 4-10 Average Energy Released per Boat Passage

Figure 4-11 shows the relationship between the wake height and energy for a large cargo boat. The energy increases exponentially with the height of the wave. All of the boat types followed this same exponential trend.

Velocity versus energy plots were also made for each boat type. Figure 4-12 shows a velocity versus energy plot for large cargo boats. The team broke down plots for each boat type by payload and then made regression lines for each boat type with these plots. The equations for the regression curves were later used to predict the energy that each boat type would release as wake at various speeds as described in the Methodology section 3.4. For example, the regression equation for speed vs. energy for large cargo boats is $y = 0.15x^{1.5}$, where x is the speed and y is the energy resulting from large cargo boat traveling at that speed. These energy values were then used in conjunction with previously collected traffic data to create the Moto Ondoso Index, which is discussed in the analysis chapter.

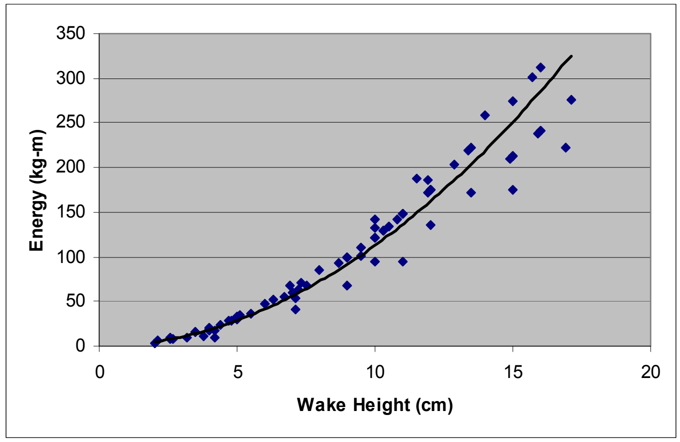


Figure 4-11 Wake Height vs. Energy for Large Cargo Boats

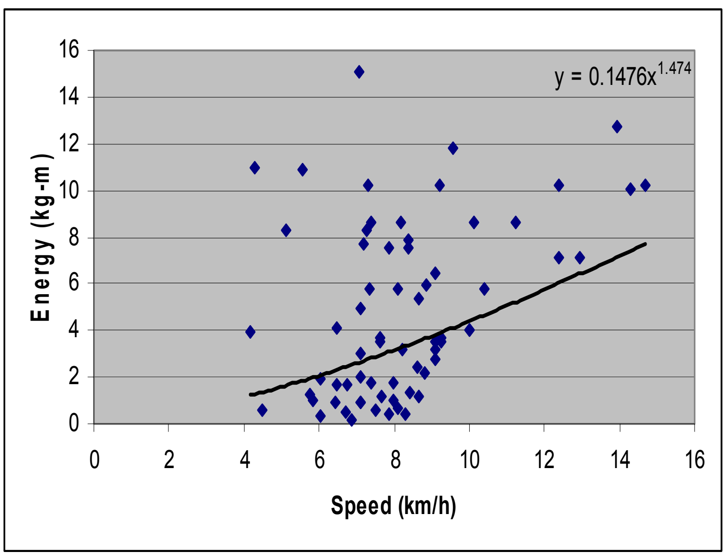


Figure 4-12: Velocity vs. Energy for Large Cargo Boats

4.6 Wake Angle (σ)

The data collected on the angle σ, was used to calculate energy values as described in the previous section. The measured values of σ were only one or two degrees within each other. For this reason, it was possible for the team to use a standard value for sigma for energy calculations. Table 4-3 lists some of the results of the angle measurements.

Boat Type	Payload	Speed	Width	Angle (σ)
taxi	high	fast	medium	30
large cargo	medium	medium	medium	31
taxi	low	medium	medium	31
large cargo	low	medium	medium	33
taxi	low	fast	medium	32

Table 4-3: Wake Angle Data

The complete data set for angle measurements can be found in Appendix B. When the data was inspected, it was clear that σ did not vary greatly with differences in speed, payload, or boat width. Most of the values of σ are close to 31 or 32 degrees; the average measured σ was approximately 32 degrees. However, the team used the value of 34.5 degrees for energy calculations. The reason for the discrepancy between the standard angle and the measured values can be explained by the method in which the angle was measured. The angle was measured by the use of a protractor held against pictures of boat wake that were taken from an elevated position. The picture was not taken from directly overhead therefore the parallax effect came into play. This made the angle measurements inaccurate by 2 or 3 degrees. This inaccuracy accounts for the difference observed between the experimental and reported values of σ, therefore the standard angle measurement of 34.5 degrees was used by the team in energy calculations.

5 *Analysis*

The following chapter presents the analysis of the results discussed in Chapter 4. The creation of the database that helped the team calculate Moto Ondoso Index (MOI) values for each canal segment also allowed us to simulate changes in traffic patterns, speeds, and regulations. If these or other variables were to change, the Moto Ondoso Index value would change appropriately to represent the change in the amount of energy released into the canal. This task was accomplished by combining traffic data with the regressed energy equations of different boat types at different speeds. These different indices let us compare how the total energy in the canal system would change if boat traffic were to fluctuate in different ways. Inspiration for possible and likely traffic scenarios included in the analysis came from the newspaper articles on the topic of moto ondoso that were printed almost every day during our stay in Venice, some of the team's hypotheses based on current traffic patterns, and the cargo warehouse project proposal. We created indices for these different scenarios to make predictions of how the canal walls would be affected by changes in traffic patterns.

5.1 Moto Ondoso Index

Spatially and temporally extended traffic data was applied as described in sections 3.4.1 and 3.4.2 of the Methodology chapter to create index values for each canal segment by boat type, and payload. A sampling of these index values are shown in Table 5-1. The segment code in this sample, ALBO, represents Rio de l'Aboro, boat codes 1 and 2 represent large and small cargo boats respectively. Payloads H, L, and M stand for High, Medium and Low respectively, and the values on the rest of the cells are the index values for the different boat types broken down by payload for Rio de l'Aboro.

Segment	Boat Code	Payload	Summer MOI at 4 km/h	Winter MOI at 4 km/h	Summer MOI at 5km/h	Winter MOI at 5 km/h	Summer MOI at 20 km/h	Winter MOI at 20 km/h	Summer MOI at Avg km/h	Winter MOI at Avg km/h
ALBO	1	High	3.2	2.6	6.0	4.9	100.9	82.2	41.4	33.7
ALBO	1	Low	63.0	51.3	85.4	69.5	625.4	509.2	326.9	266.2
ALBO	1	Medium	10.1	8.2	13.9	11.3	97.6	79.5	29.8	24.3
ALBO	2	High	1.1	0.9	3.0	2.5	204.2	166.3	204.2	166.3
ALBO	2	Low	5.7	4.7	15.2	12.4	1021.2	831.6	968.8	788.9
ALBO	2	Medium	1.0	0.8	2.6	2.1	175.1	142.6	175.1	142.6

Table 5-1: Moto Ondoso Index Values for ALBO segment for boat types 1 and 2 listed by payload and various velocities

The summation of these indices created a total Moto Ondoso Index value for the entire canal system. This was done for the winter and summer seasons to show the difference in energy between tourist and non-tourist season. The base total index values (i.e. all boats traveling at 5 km/h) for summer and winter respectively are 144.900.000 and 83.520.000. These values are the standard by which all other indexes are compared. The traffic in the summer months releases 42% more energy than in the winter months. Complete tables for the indices are in Appendix C. Figure 5-1 and Figure 5-2 show MapInfo s of the base total index values for winter and summer.

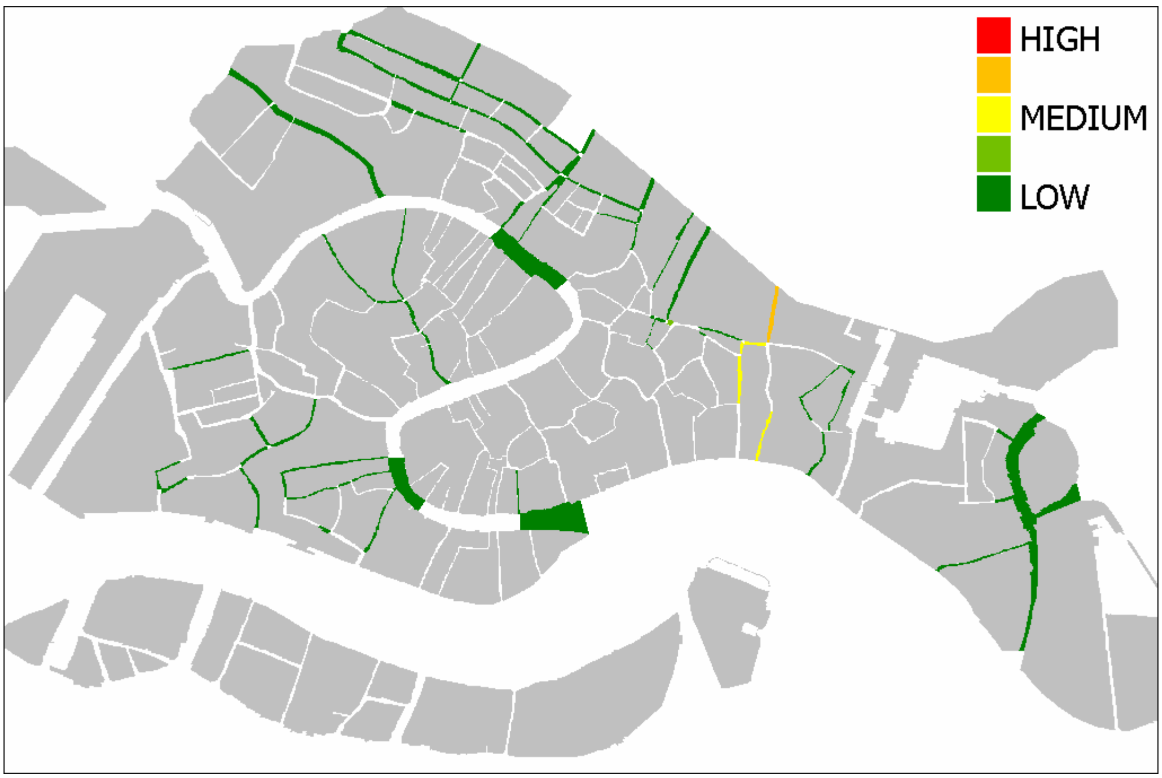


Figure 5-1 Base Index Values (Boats Traveling at 5 km/h) for Winter Season

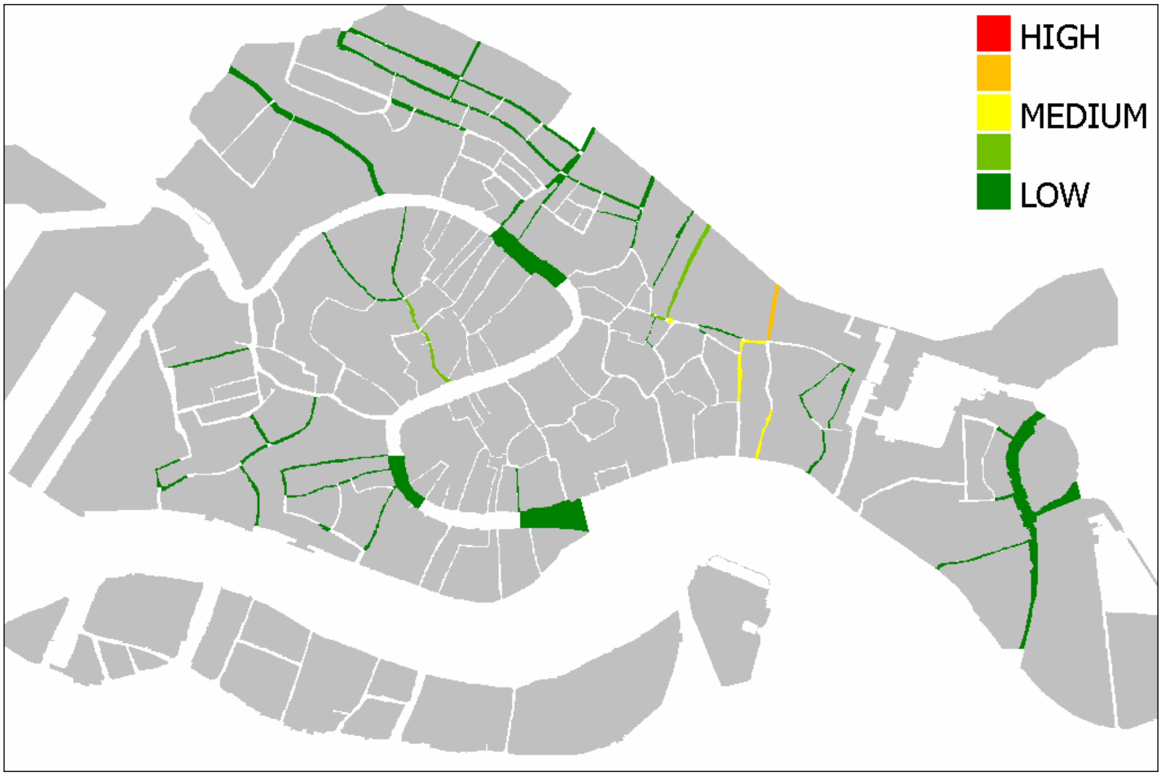


Figure 5-2 Base Index Values (Boats Traveling at 5 km/h) for Summer Season

On both maps, it is clearly shown that most of the canals have low to medium indices when boats are obeying the speed limit as indicated by the dominant area covered by green.

Index values were also broken down by boat type to see what percentage of the total index each boat type is accountable for. In the summer and winter, taxi boats have the highest base index values (the index at 5 km/h); 77.510.000 for the summer and 50.690.000 for the winter, which is 53% Of the total Moto Ondoso Index and therefore, 53% of all the energy released into the canals. **Figure 5-3** is a graph showing the base index values for different boat types in the summer season. However, when traveling at their actual average speed, small cargo boats have by far the highest index, as shown in Figure 5-4 (1.035.000.000 in summer and 631.800.000 in the winter) and accounts for 66% of the total amount of energy. On average, small cargo boats travel slightly faster than the other boats in the canals, but they also produce the largest wakes when traveling at higher speeds. **Figure 4-6** shows the trend lines for the height of wakes at different speeds. At lower speeds the wake size of small cargo boats is smaller than other boats, but this wake size rapidly increases and after the boat reaches 8 km/h it produces wakes that are larger than those of all the other boat types. Since most small cargo boats travel at or above 8 km/h (as shown in **Figure 4-2**), they are consistently producing the largest wakes all the boat types, causing their index value to be significantly higher at the speeds the boats actually travel .

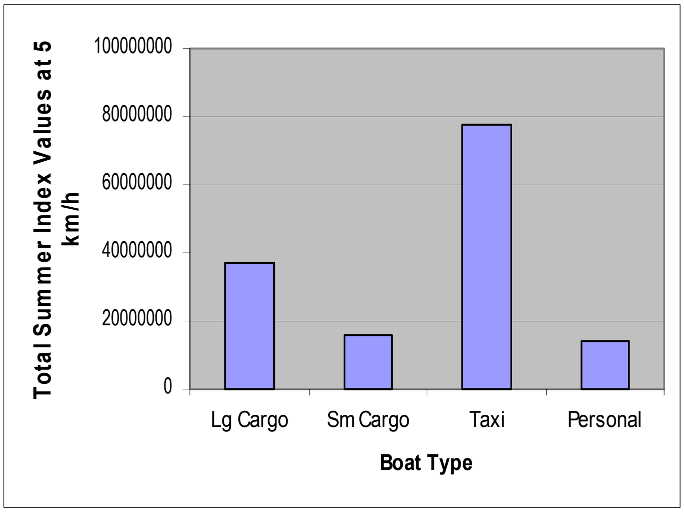


Figure 5-3 Total Summer Index Values for Different Boat Types Traveling at 5 km/h

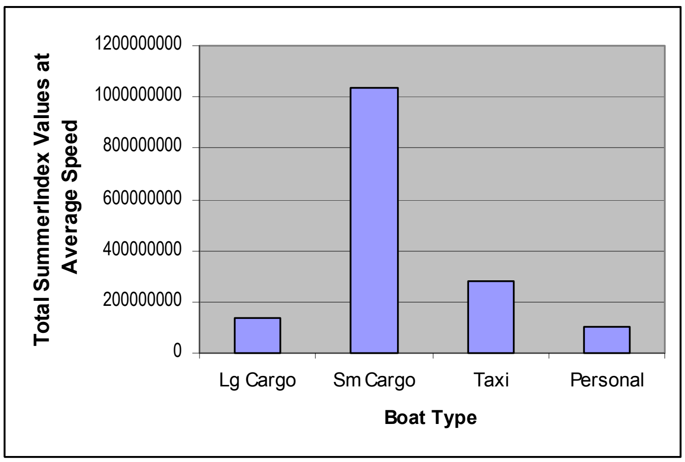


Figure 5-4 Total Summer Index Values for Different Boat Types Traveling at Their Actual Average Speed

5.2 Enforcement of Speed Limits

Speeds of moving boats within the lagoon and canals are difficult to gauge because boats lack speedometers, many people can only give their best guess as to what speed they are traveling at or they keep with the flow of traffic, as a result speeding is a common occurrence, we analyzed the effect that speeding boats have on the index. The team predicted that if speed limits were obeyed, the resulting wake would be reduced, meaning lower energy and index values. We created the total index value to reflect the amount of energy that is released into the canal system when boats are traveling at their average speed. The index value for the summer months would increase to 1.558.000.000 and 904.700.000 for the winter months. Based on this analysis, boats traveling at their current speeds release 975% more energy into the canal system then they would if they would if they were to travel at the speed limit in the summer, and 983% in the winter. Therefore, if boats were to slow down and travel at the speed limit, the amount of damage done to the canals by wake energy would also be reduced over 900%.

The team completed similar analysis for each boat type. The table of index values that was broken down by boat type and payload at different speeds was used to easily determine the index values for each boat type traveling at the speed limit for each payload category. Table 5-2 shows the index values during summer and winter for each boat type and their payloads at the average speed of travel and the speed limit of 5 km/h. Each boat type shows a decrease in index value at 5 km/h from the average speed. Table 5-3 shows the percent decrease in Moto Ondoso Index values for each boat type. The boat type with the biggest change in index value when boats traveled at the speed limits was small cargo boats with a 98% decrease in both winter and summer. This reduction is not only because small cargo boats travel on average faster than all other boat types, but because they produce by far the largest wake at high speeds. Refer to Figure 4-6 for the regression lines of small cargo boats vs. other boat types.

Boat Type	Payload	Monthly Summer MOI at 5 km/h	Monthly Winter MOI at 5 km/h	Monthly Summer MOI at AVG km/h	Monthly Winter MOI at AVG km/h
Large Cargo	High	3.319.000	2.027.000	22.920.000	14.000.000
Large Cargo	Low	25.860.000	15.790.000	99.000.000	60.460.000
Large Cargo	Medium	7.982.000	4.875.000	17.180.000	10.490.000
Small Cargo	High	1.209.000	738.700	81.030.000	49.490.000
Small Cargo	Low	13.570.000	8.290.000	862.600.000	526.800.000
Small Cargo	Medium	1.357.000	828.600	90.890.000	55.510.000
Taxi	High	586.000	383.200	7.280.000	4.761.000
Taxi	Low	76.100.000	49.770.000	259.500.000	169.700.000
Taxi	Medium	818.300	535.100	17.510.000	11.450.000
Personal	High	27.460	551	48.880	981
Personal	Low	13.890.000	278.700	98.900.000	1.985.000
Personal	Medium	215.600	4.326	815.500	16.370

Table 5-2 Summer and Winter Indexes for 5 km/h and Average Speed

Boat Type	Percent Summer	Percent Winter
Large Cargo	73%	73%
Small Cargo	98%	98%
Taxi	73%	73%
Personal	86%	86%

Table 5-3 Percent Decrease in MOI if Boats Slow Down to 5 km/h

Figure 5-5 and Figure 5-6 show the index values of boats traveling at their average actual speeds within the canals. If boats were to follow the speed limits the index values in these maps would be reduced to those in Figure 5-1 Figure 5-2, which are considerably lower.

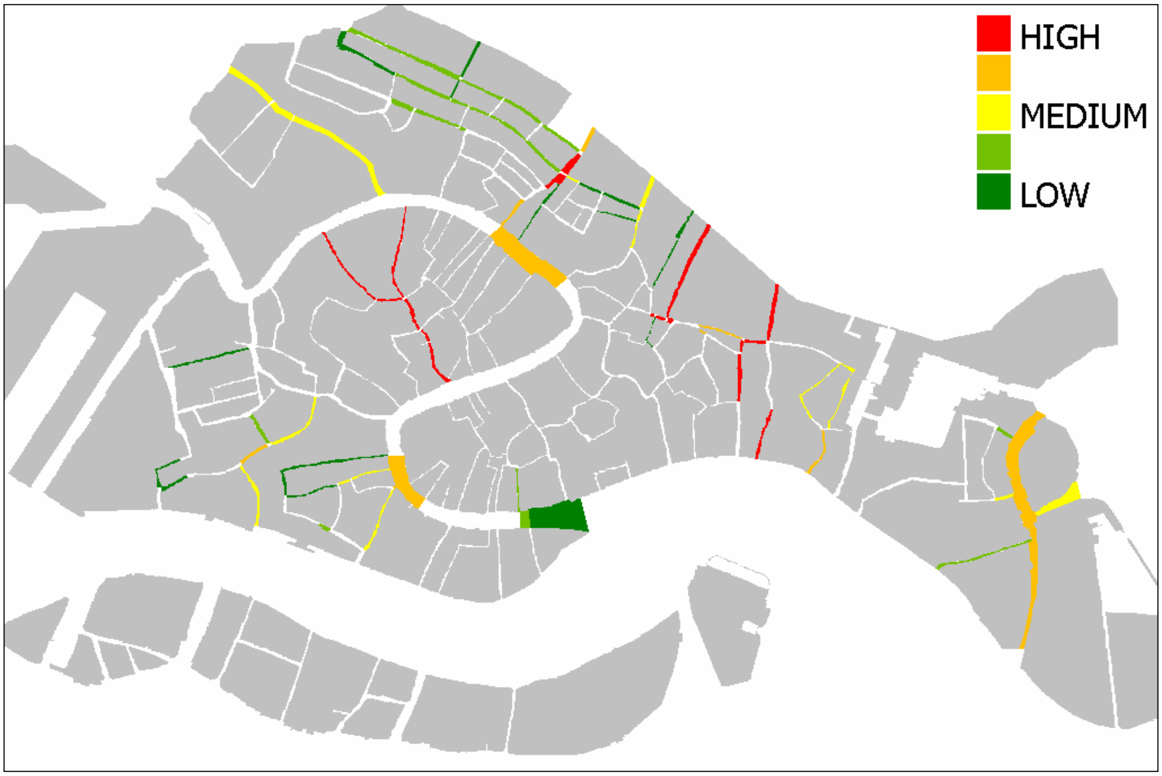


Figure 5-5 Index Values for Boats Traveling at Actual Average Speeds, Summer

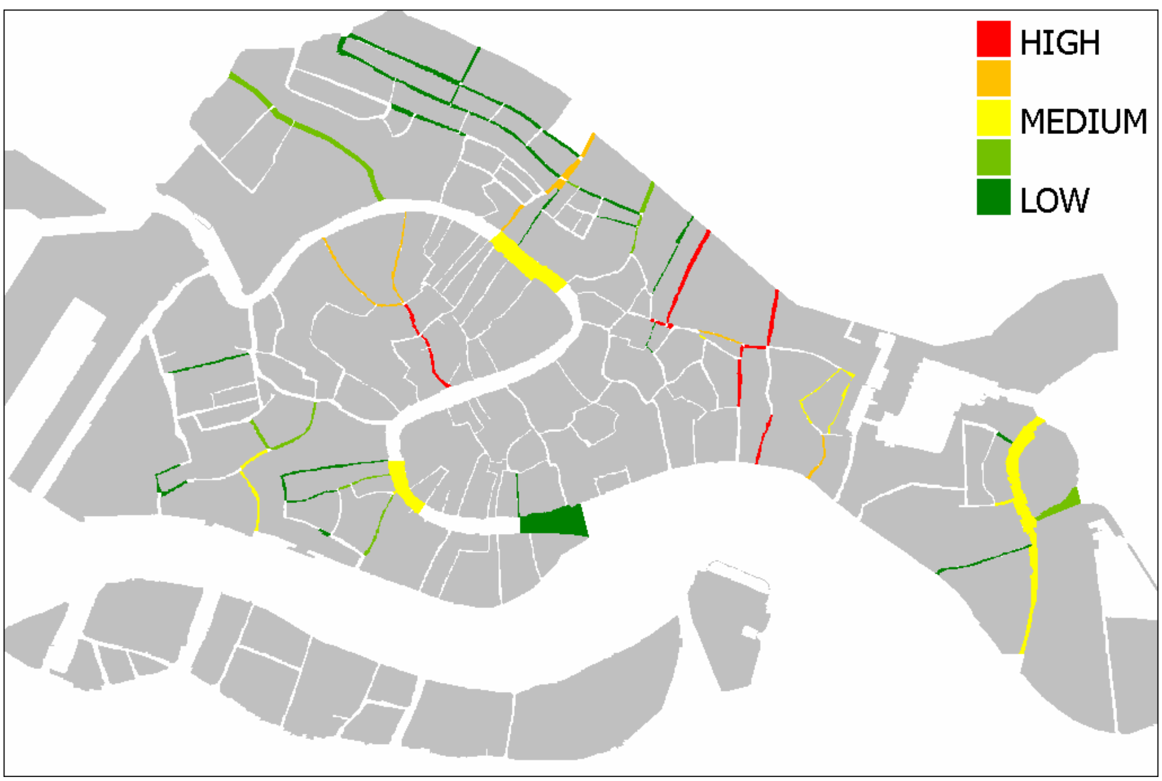


Figure 5-6 Index Values for Boats Traveling at Actual Average Speeds, Winter

5.2.1 Speed Limits of Taxi Boats

In a recently published newspaper article[35] taxi boat drivers were reported to be requesting a 40% increase in their speed limits; from 5 km/h to 7 km/h. According our data, taxi boats are currently traveling at an average speed of 11.7 km/h; much higher than the 7 km/h they are requesting. In the summer months, taxi boats traveling at their average speed release more than 2.5 times the amount of energy they would if they traveled at the speed limit (with an index of 284.300.000 at average speed vs. 77.510.000 at 5 km/h). If taxi boats were to travel at 7 km/h rather than 5km/h the Moto Ondoso Index value for taxi boats as a whole would increase by 80% from 77.510.000to 139.100.000. Figure 5-7 and Figure 5-8 show how the index values of taxi boats would increase if their speeds changed from 5 km/h to 7 km/h.

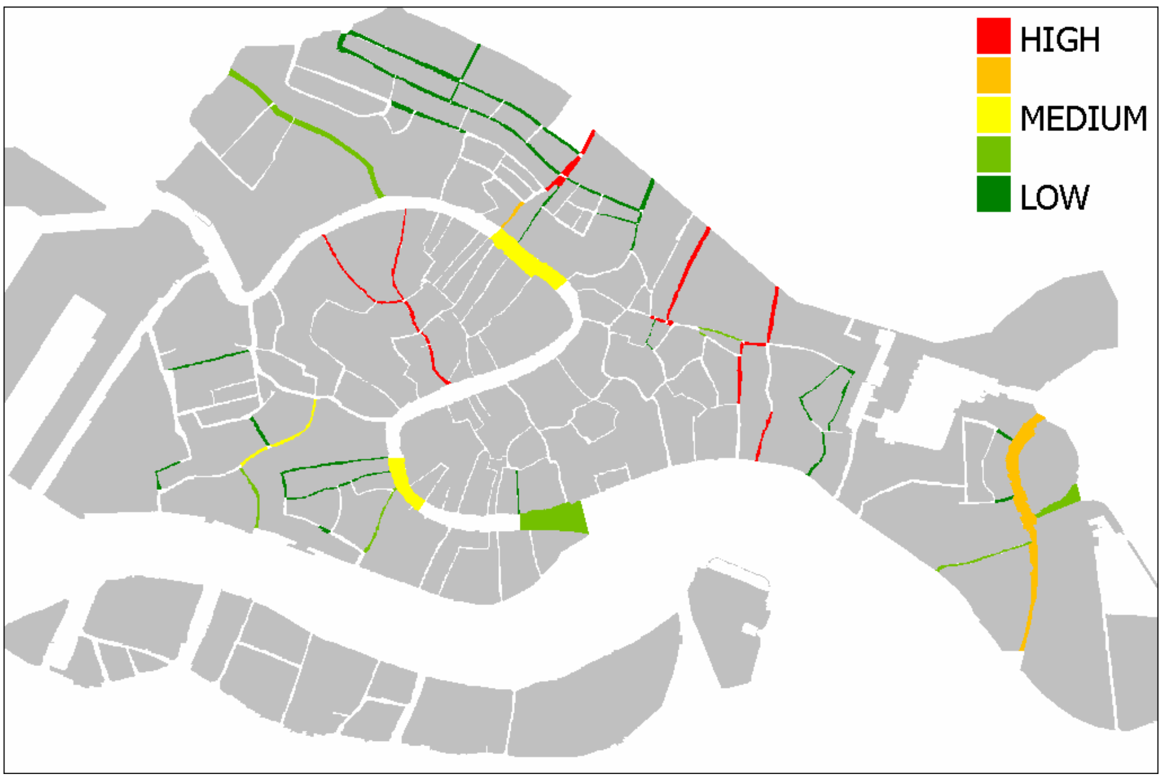


Figure 5-7 Taxi Boat Index Values When All Boats Travel at 5 km/h, Summer

[35] Testa, Slivio,, "I Motoscafisti Rilanciano" Il Gazzettino; 19 Luglio, 2002.

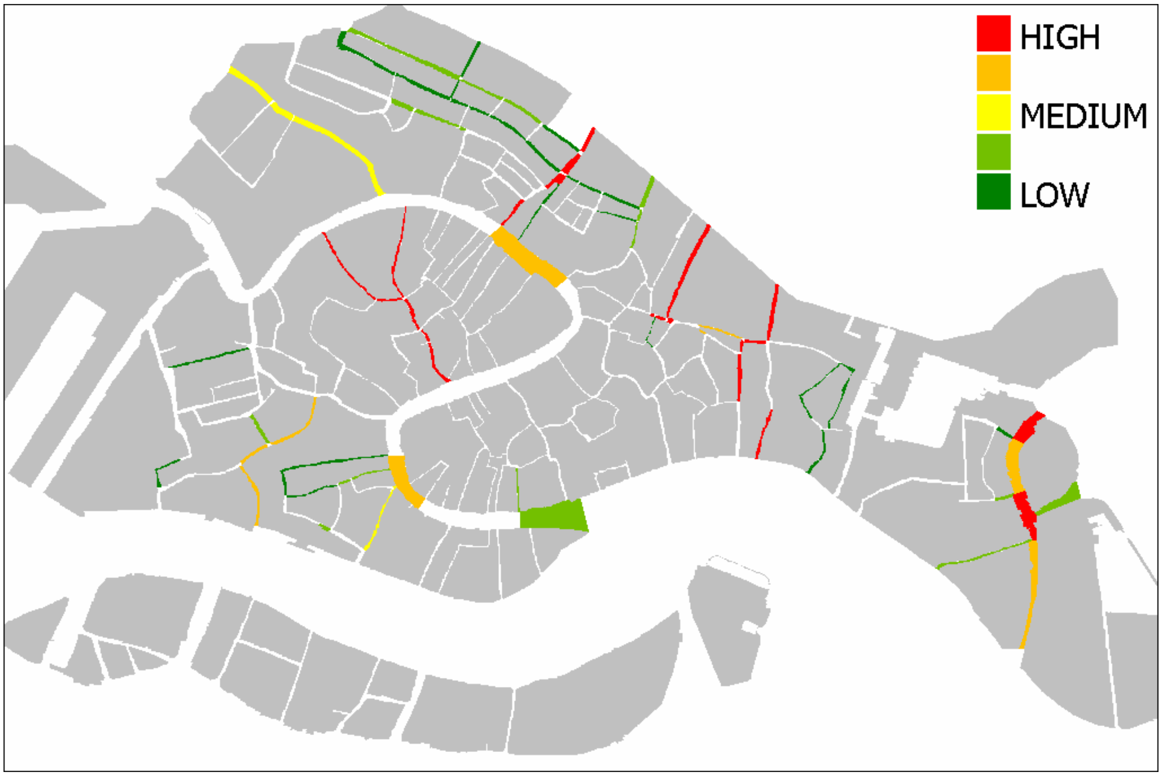


Figure 5-8 Taxi Boat Index Values When All Boats Travel at 7 km/h, Summer

However, since most taxi boats already travel faster than 7 km/h, the likelihood of them abiding to the new regulation would be very slim. An increase in the speed limit may tempt taxi boat drivers to increase their average speed even more. To simulate this increase of average speed, the team increased the current average speed of taxi boats (11.8 km/h) by 40 % to be 16.5 km/h and recalculated the Moto Ondoso Index. The new index values for boats traveling at a new average speed of were 278.100 for the winter, and 318.900 for the summer; an increase in energy of 40% of the energy they are already releasing into the canals. Figure 5-9 shows the index of all boat types traveling at their average speeds, and Figure 5-10 shows the index if the average taxi boat speed were to increase by 40%. Taxi boats travel familiar routes around the city, so even though not many of the canal segments are affected, those that are affected are increased considerably. This sort of traffic pattern can lead to severe destruction to particular areas or buildings, as discussed in Section 2.2.2.

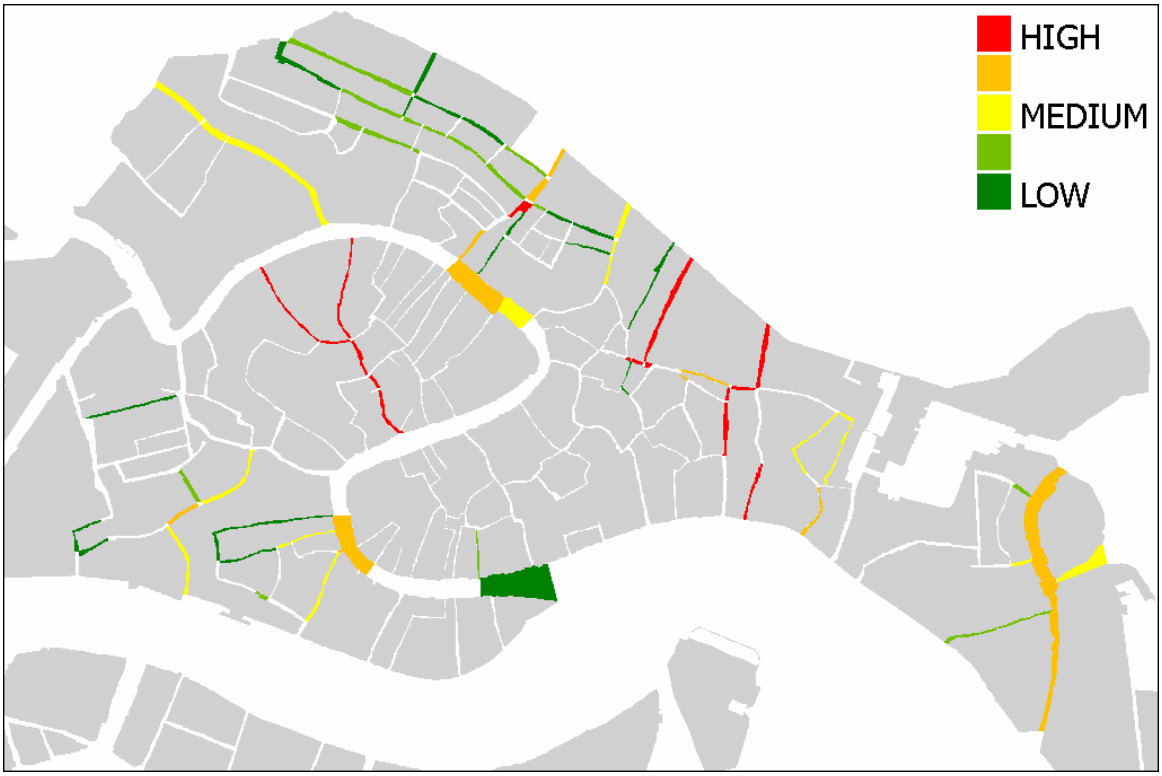


Figure 5-9 Total MOI at Average speed, Summer

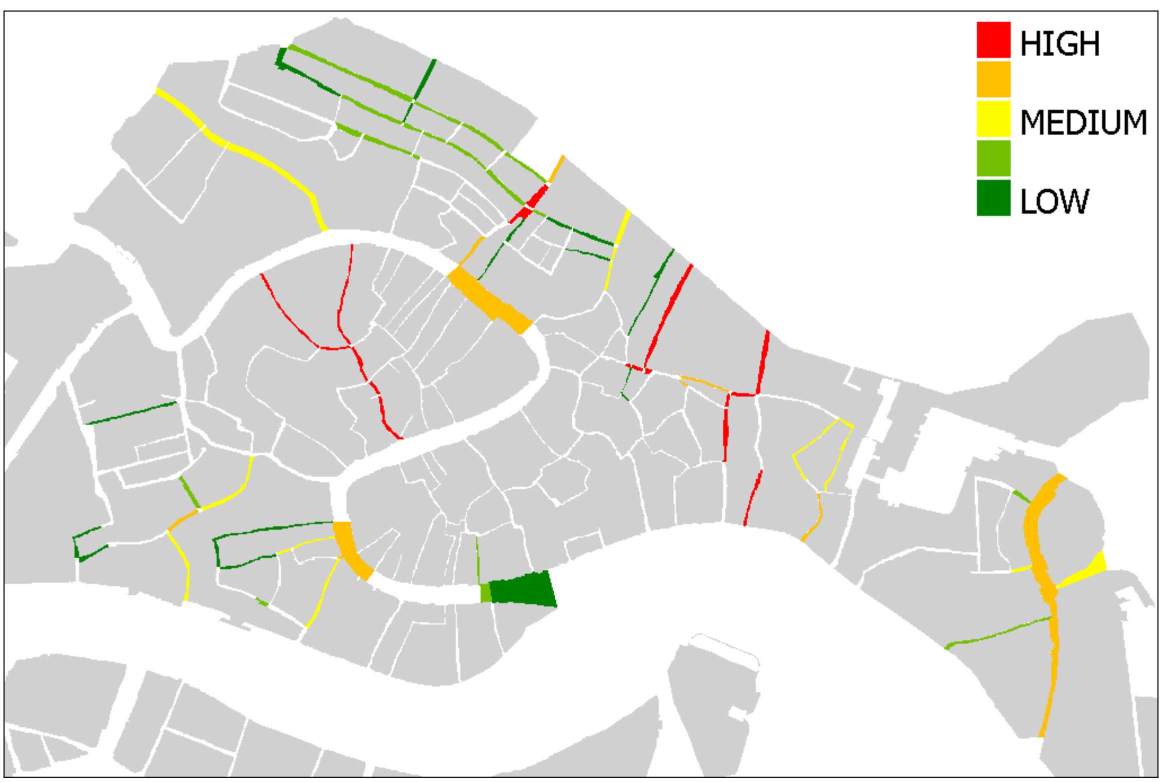


Figure 5-10 Total MOI with Taxi Boats Traveling at 140% of Average Speed (16.5 km/h), Summer

5.3 Regulating Taxi Boat Numbers

Due to the large number of taxi boats in the canals in the summer months we simulated the implementation of regulations limiting the number of taxi boats in the canals. The increase in the number of tourists in summer months creates a 14% increase in taxi boat travel. This increase in taxi boat travel causes a 5% increase to the total base index of the canals system. Every year 230 taxi boat licenses are issued in Venice so at any given time there can be up to 230 taxi boats operating in the canal system. In addition to these taxi licenses, approximately 50 extra licensees are issued for use in the lagoon, but not in the inner canals. Many of these taxi boats disobey the restrictions of their license and operate within the inner canals, causing an increase in taxi traffic. As shown in Section 5.1, the Moto Ondoso Index value for taxi boats in the summer months is 77.510.000. If regulations were made to reduce the current number of taxi boats by eliminating illegal operators the index value would change. To approximate this change, we calculated a 25% reduction on summer taxi boat travel. The resulting index value for summer taxi boats would be 5.813.000. Figure 5-7 shows the base index value for taxi boats, and Figure 5-11 shows what index values would likely be if illegal taxi operations were eliminated. By eliminating illegal operators with stricter regulations and limiting the number of operating taxi boats in the canals during summer, the amount of energy released into the canals would be reduced, slowing and reducing damage done to canal walls.

5.4 Reduction of Cargo Boat Traffic

An important scenario that we analyzed involved the amount of cargo boat traffic in the canals. Since the city needs the materials carried by these cargo boats all year round, the number of cargo boats in the canals does not vary as much as other boat types do from summer to winter. The increase of cargo boats during the summer months is necessary to keep businesses well stocked to meet the demands of the tourist season. However, the current system of cargo delivery has been proven to be inefficient, using more boats than necessary.[36] The project completed in the summer of 2001 on the re-engineering of Venice's cargo delivery system developed a system that would organize cargo boat deliveries by destination instead of cargo, reducing the total amount of cargo boat traffic in the inner canals by 90%. We calculated what the index values for the summer season would be if this plan were implemented as shown in Table 5-4. At 5 km/h the total index dropped 33% and at the average speed the index dropped 68%. Figure 5-1 and Figure 5-2 show the base MOI values with.

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[36] Re-Engineering The City OF Venice's Cargo Delivery System, IQP, 2001.

	5 km/h	Average Speed
Total Index	144.900.000	1.558.000.000
Total Index With 90% Reduction In Total Cargo Boat Traffic	96.970.000	501.400.000

Table 5-4 Index Values with a 90% Reduction in Cargo Boat Traffic

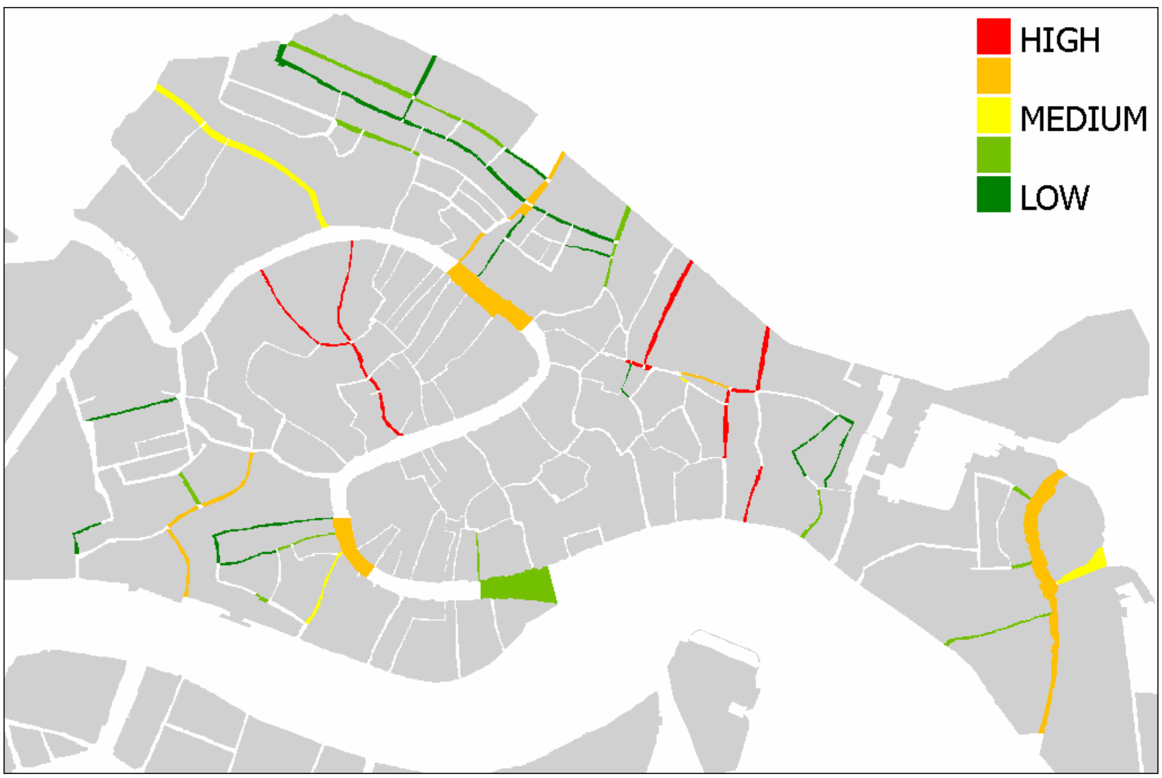

Figure 5-11 Simulation of Index Value for Taxi Boats with Elimination of Illegal Taxi Operations

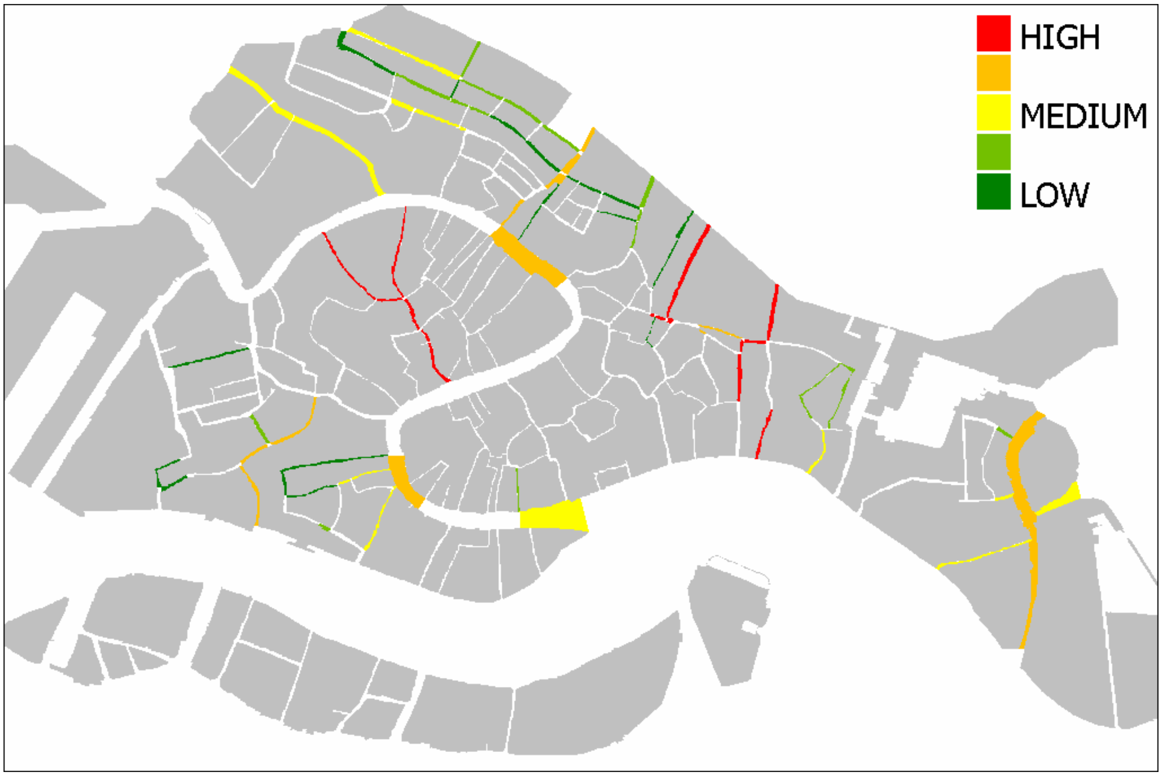

Figure 5-12 MOI Values After 90% Reduction in Cargo Boat Traffic, Summer

5.5 Future Index Values if Current Traffic Growth Continues

Every year, the amount of total traffic traveling the canal of Venice increases by 2.5%.[37] The increase in traffic creates an increase in index value for the entire canal system. We used this percent increase to project how the index values would change over the next five and ten years if no new traffic regulations or significant changes in traffic flow occur within these time periods. Within five years the index would increase by 13% to 169.700 in the summer and 107.600. In ten years the summer indexes will increase to 192.100 and 121.900 respectively, with a total increase of 28% as shown in Figure 5-14, which shows current summer base index values, and Figure 5-15 and Figure 5-16 show projections for summer traffic in 2007 and 2012. The same projections for the winter months are depicted in Figure 5-17 and Figure 5-18.

	Summer	Winter	% Increase From 2002
Total Base MOI 2002	150.000	952.30	
Total Base MOI 2007	169.600	107.600	13%
Total Base MOI 2012	192.100	121.900	28%

Table 5-5 MOI Values and % Increase in 5 and 10 Years

[37] Caniato, Giovanni; Carrera, Fabio; Giannatti, Vicenzo; Pypert, Philippe: Venezia la Cotta Dei Rii, 1999.

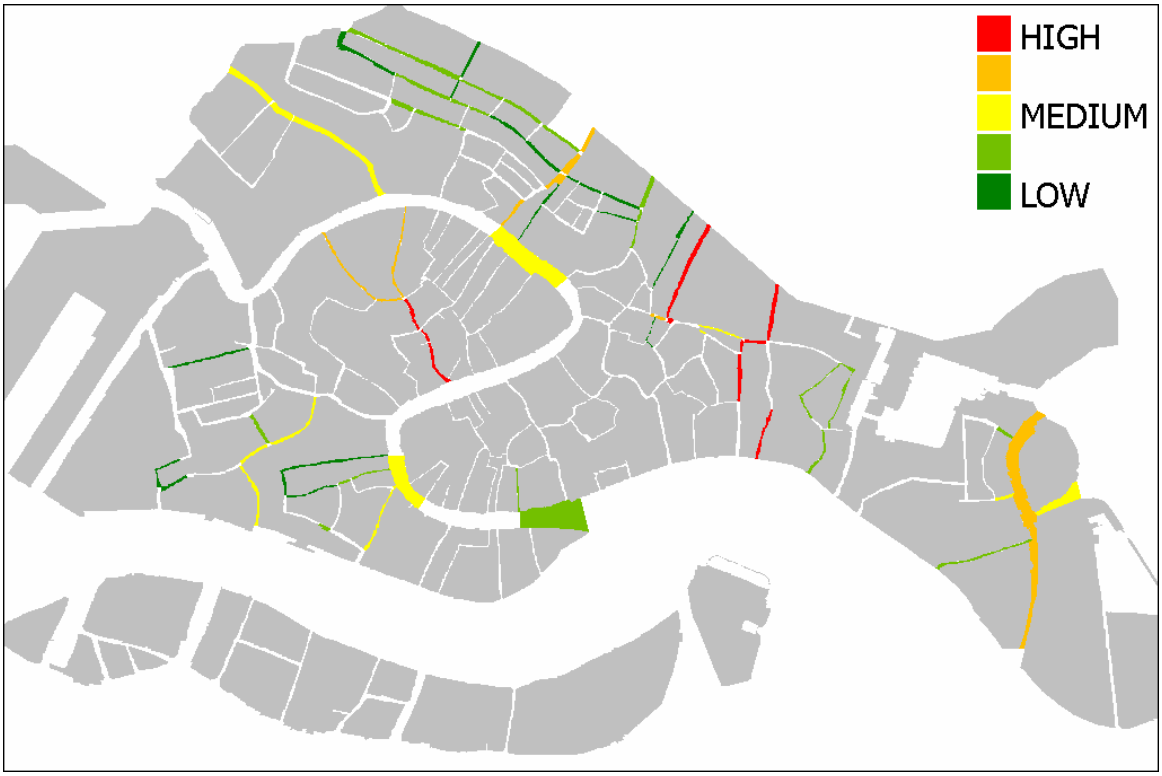

Figure 5-13 MOI Values After 90% Reduction in Cargo Boat Traffic, Winter

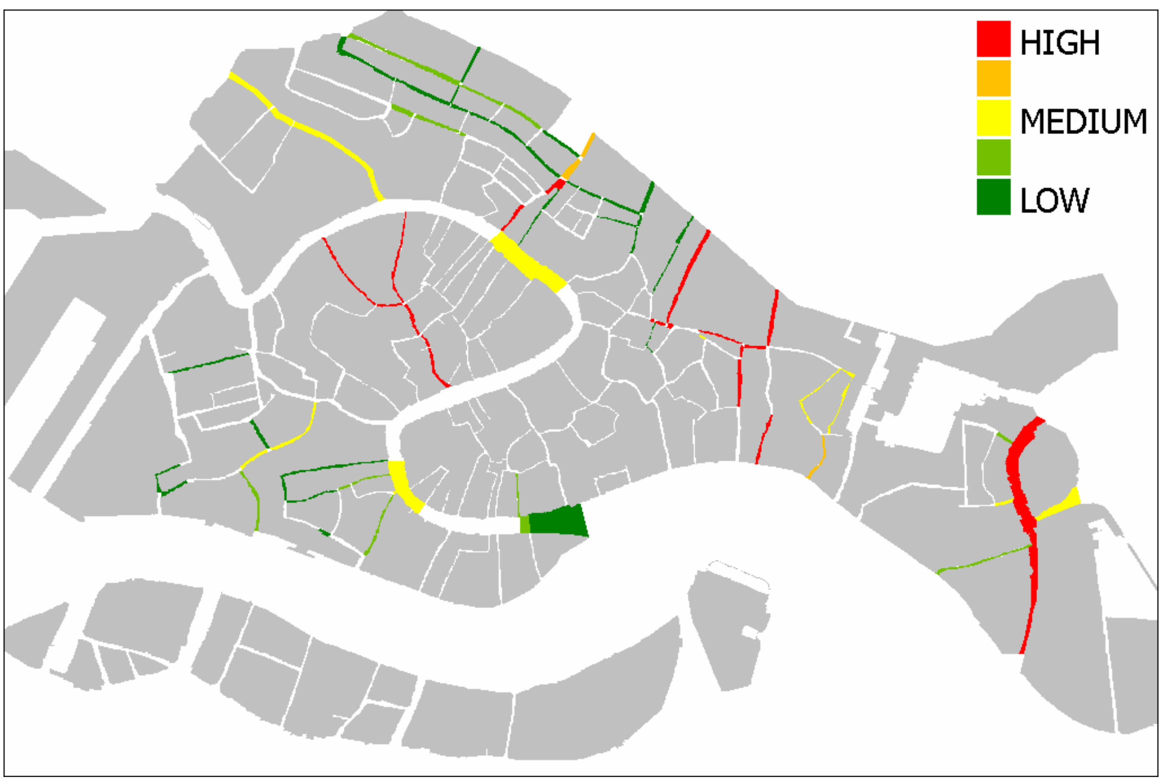

Figure 5-14 Base Index Values, Summer 2002

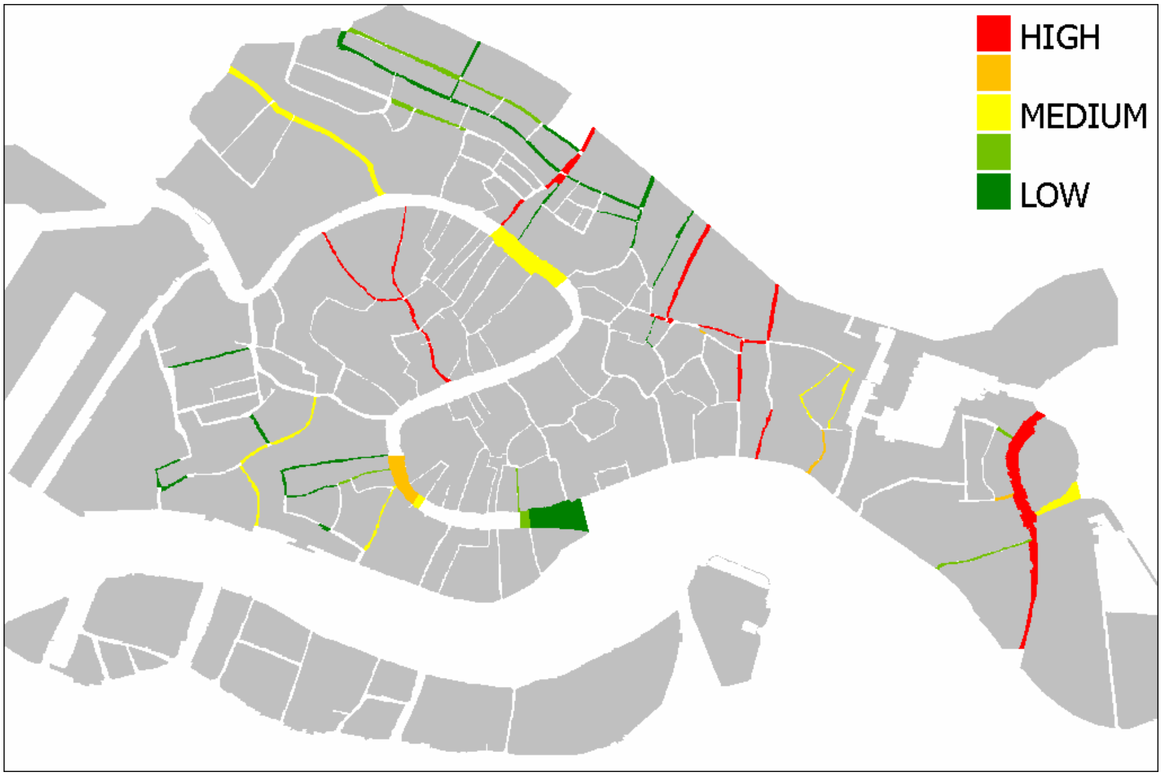

Figure 5-15 Base Index Value Predictions, Summer 2007

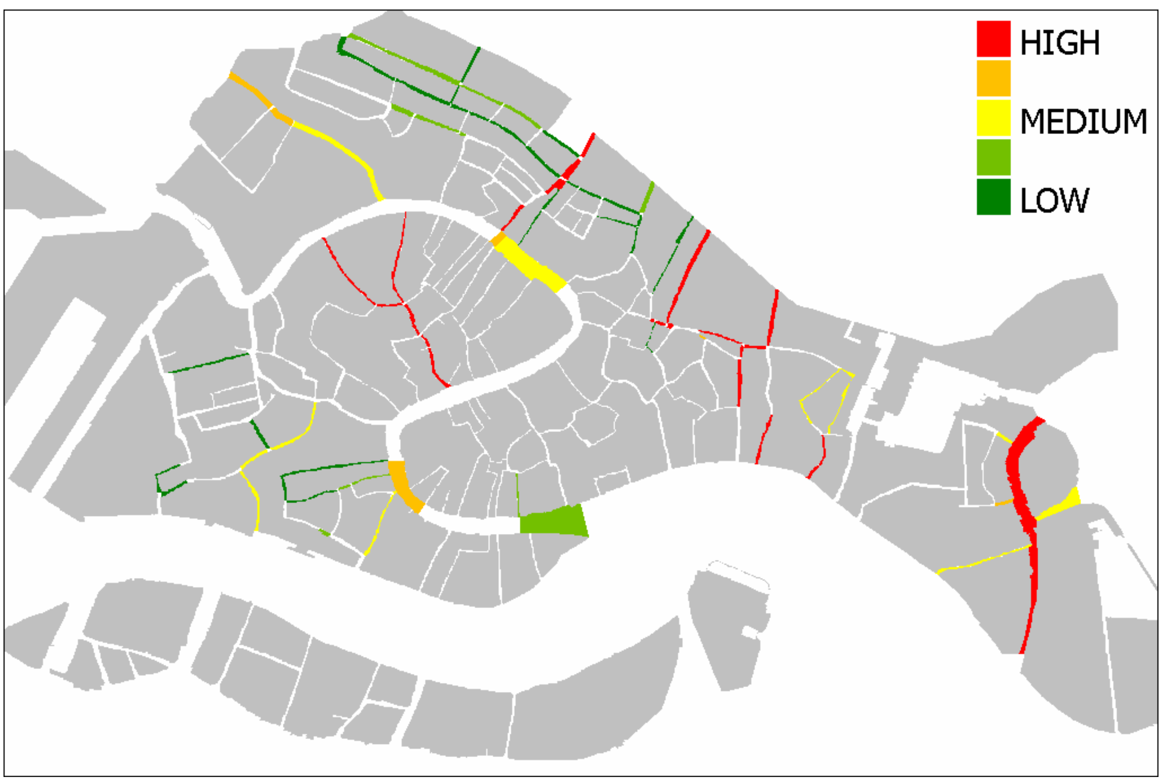

Figure 5-16 Base Index Value Predictions, Summer 2012

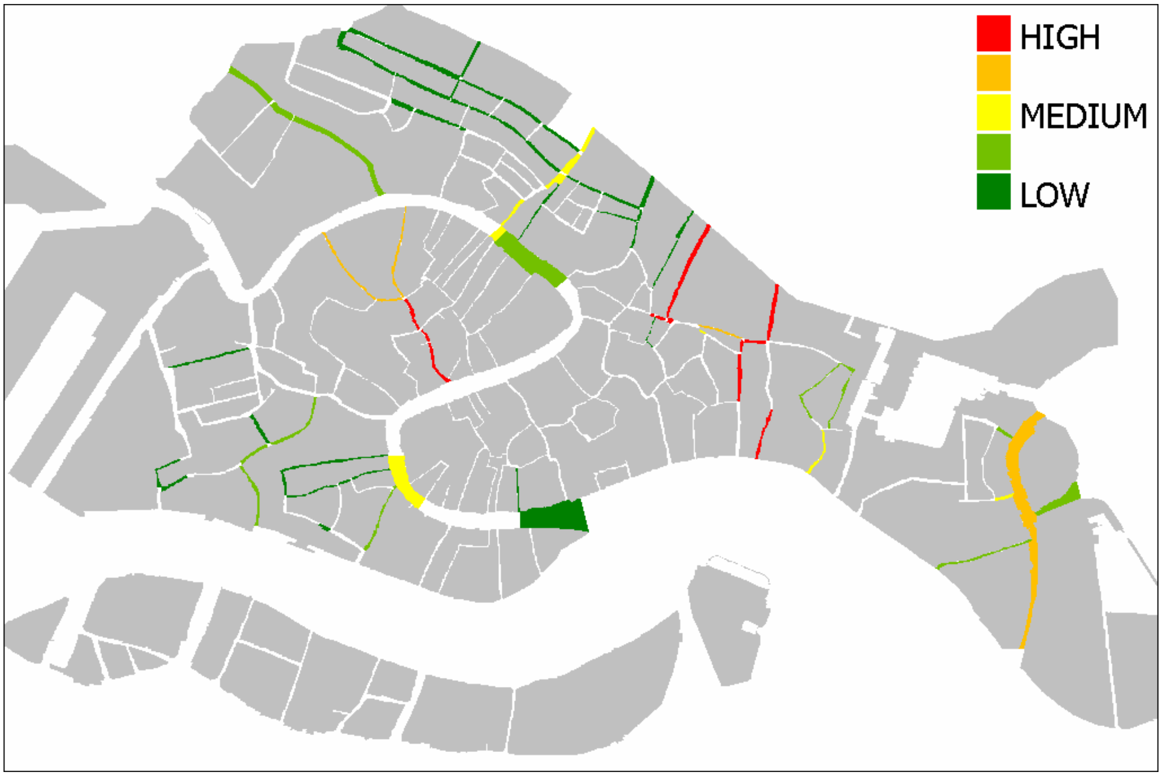

Figure 5-18 Base Index Values, Winter 2002

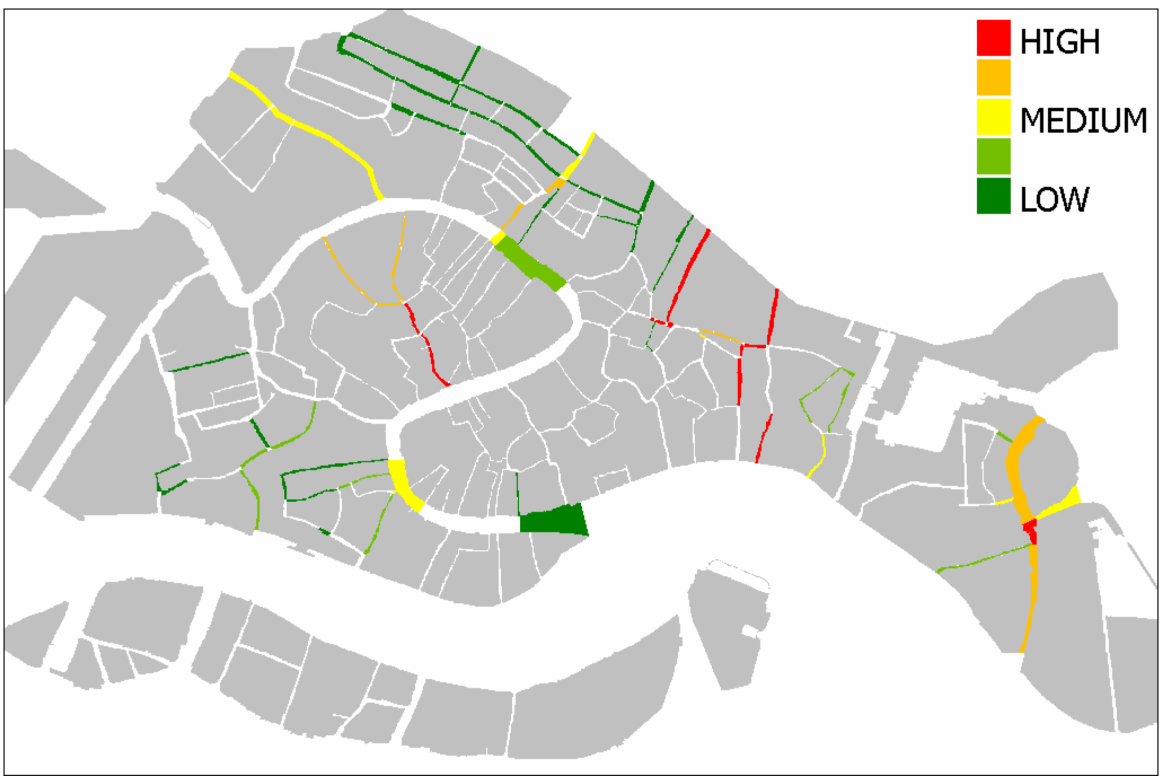

Figure 5-17 Base Index Value Predictions, Winter 2007

These maps show that if no action is taken to lower index values, the damage rate of canal walls will increase considerably within the next ten years, and could put the city of Venice in danger.

6 Conclusions and Recommendations

The following chapter contains conclusions of the team's study of Moto Ondoso, and proposals we developed to combat the problem of canal wall damage in the canals of Venice. Some of the key problems associated with motorboat traffic are discussed, followed by our recommendations for alleviating these problems. We hope that the CTVR, *Pax in Aqua,* and the City of Venice will further investigate and possibly implement the proposed solutions.

6.1 Conclusions

This chapter presents factors caused by motorboats we believe to be causes of the consistent damage done to the canal walls in Venice.

6.1.1 Disobeying the Speed Limits

Upon examination of the speed data, it was clear that motorboats do not obey the speed limits set for the canal system. Figure 4-3 in the Results chapter shows that only 3% of boats follow the posted speed limits and 13% travel within 2 km/h of the speed limit. For example, taxi boats travel at an average speed of 11.7 km/h; almost 7 km/h over the set speed limit of 5 km/h. As boats continue to increase speed over the speed limits, the amount of energy they release into the canals increases exponentially. This excess energy is one of the primary causes of the rapid canal wall disintegration.

There are a few possible causes for the vast disregard of the speed limits. The recent implementation of the current speed limits for the entire Venetian lagoon could be a reason for the speeding. [38] The residents may not have had time to adjust or are not fully aware of the regulations. Also, speed limits are most strictly enforced in the Grand Canal, so boat drivers have no motivation to follow the laws or change their habits elsewhere. Many Venetian industries such as taxis and cargo delivery rely on speed to be profitable. Drivers of these types of boats are reluctant to slow down to obey the speed limits, because doing so would sacrifice productivity and subsequently money.

6.1.2 Boat Types Responsible for Most Energy Output

After calculating at total Moto Ondoso Index value for the canal system, the team was able to determine that small cargo boats are responsible for most of the energy released into the canals, contributing 66% of the total energy released by boats traveling at their respective average speeds.

[38] speed limits were set between late December 2001 and early January 2002

Taxi and large cargo boats have the second and third highest index values contributing 18% and 9% of the total energy.

6.1.3 Traffic Congestion

Congestion is another major factor in the damage to canal walls. Not only does congestion mean that there are more boats in the canals, but congestion forces boats to maneuver more often than they otherwise would and maneuver in manners other than they normally would. When boats are forced to continuously stop, start and maneuver they are releasing exorbitant amount of turbulence. They are also forced to maintain their position in the canal for an extended period of time while they wait for clear passage creating more turbulence than if they had continued on through the canal.

Congestion is caused not only by the large number of boats, but by the inefficient traffic patterns of certain boat types. Cargo boats travel all over the city making many stops in order to complete their deliveries. It is common to see a cargo boat unloading at a dock and one or two other cargo boats waiting in line to unload, as well as other boats attempting to maneuver around the traffic jam. Taxi boats also travel through out the canal system all day making multiple stops. These are fairly large boats, but are commonly forced to travel in narrow, winding canals in order to reach their destination, leaving little room for other boats. In the summer the large volume of tourists creates an extremely high amount of taxi traffic, sometimes over 750 boat passages[39], making the system even more inefficient. It is not unusual to see a line of taxi boats slowly trying to pass through a canal, each carrying only a few passengers.

Although gondolas create miniscule turbulence, they are a factor in the city's congestion problem. Through the year, but especially during peak tourist season there are a large number of gondolas traveling the canals. Gondolas move very slowly and back up traffic of other boat types. Also, since gondolas are used for sightseeing, large numbers of them tend to slow down or even stop in some of the scenic areas around the city. This traffic jam forces motor boats to wait for the blockage to clear before they can continue on their way or end up maneuvering around the gondole.

Analysis done with the Moto Ondoso Index showed that congestion in the canals causes an increase in the amount of energy released into the canals. Total index values were calculated for the summer and winter months. During the summer months, boat traffic increases with warmer weather and an increase in tourists. The increase in traffic, particularly of taxi and personal boats, causes

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[39] Carrera Fabio. "Il Traffico Acqueo ne Canal Int"Il Traffico Acqueo ne Canal Intern di Venezia" 10, July, 1996

congestion in the canals during summer. The index values were found to increase from 904.700.000 in the winter to 1.558.000.000 in the summer; a 72% increase.

6.2 Recommendations

The conclusions made in the previous sections, helped the team to come up with some possible methods of combating the canal damage problems. These recommendations include enforcing speed limits, regulating and rerouting the traffic patterns of selected boat types, limiting the number of boats of any particular type in the canals, and implementing the proposal of the central cargo warehouse. Other recommendations were made regarding ways this project could be done more accurately in the future through the improvement of pieces of data we used. By following the proposed plans of action discussed below, the city of Venice can avoid the 28% increase in total wake that would otherwise occur in the next ten years.[40] An increase in energy of that magnitude would damage the canal walls supporting the city at a much faster rate, placing the city and its inhabitants in danger of losing their businesses and homes.

6.2.1 Enforcement of Speed Limits

Enforcement of the speed limits by the appropriate authorities would increase adherence and would greatly reduce the amount of damage done to the canal walls. Any decrease in boat speed within the canals would result in smaller wakes and less turbulence, and therefore the amount of energy that impacts the canal walls. An example of this scenario was illustrated in Section 5.2 where the percent decrease of index values by boat type was calculated if boats travel within speed limits. The index value for small cargo boats would decreased by 98% if they were to travel at 5 km/h. A decrease in index values is equivalent to decreasing the energy released into the canals, which would in turn lead to a decrease in the rate of canal wall damage. We recommend that the speed limits in the inner canals be enforced more strictly to reduce the damage done to the canal walls.

A system of enforcing speed limits in the Grand Canal that has proven to be effective is confiscation. Boat confiscation is especially threatening to cargo and taxi boat drivers because the loss of their boat for even a week means a great loss in money and or customers. If speed limits were enforced in other canals in the city in the same manner as in the Grand Canal, boats would be likely to comply, reducing canal wall damage. The funds for canal wall repair costs come from resident taxes, so ultimately the boat drivers would benefit from their slower travel through the reduction of city taxes.

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[40] see Analysis chapter, Section 5.5

A way of making people aware of their speed infractions we suggest is to place boat speed indicators on the sides of canals that would display the speed at which boat drivers are operating their boats as they pass. This may help the citizens who are still adjusting to the recently implemented speed limits adjust their speed accordingly. See Appendix P for a diagram illustrating the boat speed indicator.

Taxi and cargo boat drivers would suffer economically if they were forced to travel more slowly, and are therefore very resistant to the speed restrictions. Taxi boat drivers would lose customers because they would take longer to reach their destinations, and cargo boat drivers would require much more time to complete their daily deliveries. Vaporetti drivers also exceed the speed limit in order to avoid falling behind the tight boat schedule.

6.2.2 The Proposed Cargo Warehouse

Currently, cargo boat drivers follow routes that take them through the entire city with only one type of cargo. It takes on average, 160 minutes to cover 19 stops throughout the historical center.[41] The amount of time it currently takes for cargo boats to deliver their goods is attributable to the traffic jams and congestion they encounter and cause. The project completed in 2001 proposed re-organizing the cargo delivery system that would involve the construction of a central cargo warehouse. This system would eliminate 90% of cargo boat traffic, which would significantly reduce the rate of damage to canal walls, not only through the reduction of traffic, but through a great decrease in the congestion that these boats cause.[42] As shown in Section 5.4 in the Analysis chapter, the total Moto Ondoso Index value calculated for all boats at 5 km/h was reduced by 33% after reducing the cargo boat traffic by 90%. Similar analysis done at the average speed of all boats showed a 68% decrease in the index value. We recommend that the cargo warehouse proposal; completed in 2001 be implemented as soon as possible to avoid unnecessary energy that is currently being released into the canals daily. The implementation of this project will be a large step towards reducing the amount of canal wall damage in Venice. See Appendix M for the complete proposal made in the aforementioned project.

6.2.3 Taxi Boat Restrictions

Taxi boat numbers vary from season to season, the highest population of taxi boats being in the summer months; tourist season. It is during tourist season that taxi boat traffic patterns need the most regulation because of their high population. Routes could come from a system utilizing Global

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[41] Re-Engineering The City OF Venice's Cargo Delivery System, IQP, 2001. pg. 14

[42] Ibid. pg. 102 - 116

Positioning Systems (GPS) in combination with a Geological Information System (GIS) to automatically find the shortest routes or the fastest routes and at the same time keeping in mind which canals are closed and which canals have a Moto Ondoso Index. Seeking alternative routes to canals with a high traffic flow would alleviate congestion in the canals. Also, some taxi boats that operate during the summer months do so illegally. Their licenses are valid, however, they are only licensed to operate in the waters of the lagoon and not in the inner canals. These boats disregard the restrictions on the licenses and operate in the canals. Removing these taxi boats from the canal system would decrease the Moto Ondoso Index value. To help this, we recommend that unique license tags e placed on taxi boats that are not permitted to operate in the inner canals. This way, taxi boast violating the spatial coverage of their licenses can be easily identified and punished by the appropriate authorities. The reduction of the Moto Ondoso Index value would redue the rate of canal wall damage.

6.2.4 Improve Traffic Data

The traffic data used in this study was out of date and spatially insufficient. Temporal and spatial extensions of the data had to be completed to bring it up to date before Moto Ondoso Indices could be created. The extension of the traffic data was done using the help of other traffic studies done on the Venetian canals, which had gaps in their information, and counts that did not accurately represent the traffic in the city. These studies were completed using a modification of a methodology spelled out in a past WPI traffic projects. The methodology in these projects described how to take traffic counts that would accurately represent the city of Venice including locations, boat types, and payload. The studies used to extend the traffic data we used did not completely follow the methodology described in the past WPI project and was therefore inaccurate to a certain degree. We recommend that accurate traffic counts be conducted more often to keep traffic data updated. Newly collected, accurate traffic data that has a good scale for payload and time of day can be used to recalculate Moto Ondoso Indices regularly so that up to date simulations of current scenarios can be conducted. If these simulations can be conducted more often with more accuracy, appropriate regulations can be instated to control the amount of wake energy and canal wall damage in the inner canals.