Spatiotemporal Analysis of Tsunami Vertical Evacuation:

A Case Study of the Shizuoka Metropolitan Area

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Spatiotemporal Analysis of Tsunami Vertical Evacuation: A Case Study of the Shizuoka Metropolitan Area

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Abstract

The city of Shizuoka is the capital city of the Shizuoka prefecture is located in central Japan. The geographic position of the city gives it a special role in the area, as major transportation networks such as rail and highways that connect North and South Japan go through the city constituting it a central node in Japan's Geography. At the same time, the city directly faces the Nankai Trough, which is expected to give a major tsunamigenic earthquake every 100 to 200 years. A tsunami generated by such an earthquake could have major implications to the lives of the city's residents, even from the very first moments of the tsunami when they will need to escape. As such, there is a need to study the potential for a vertical evacuation in the city in order to provide multiple options for safe refuge in such an event.

This study has the main objective of finding vertical evacuation sites among the currently existing buildings in the city, an approach that allows fast results in the face of immediate danger, and to analyze their potential for vertical evacuation by examining how these buildings become inundated under variable tsunami scenarios, and how the city's population moves throughout them in different times of the day leaving increased or decreased volume available for evacuation. A wide range of Geographic Information System (GIS) datasets, as well as demographical and people flow movement data were used in order to (a) calculate the inundation ratio of buildings in Shizuoka City, (b) calculate the volume loss of buildings due to tsunamis based on the inundation ratio, (c) estimate the building population of the buildings in Shizuoka over 24 hours of the day and (d) introduce criteria per tsunami scenario in order to estimate how many people can be accepted in each building for evacuation based on the variable population.

The approach of this research has indicated that for four different tsunami scenarios (5m, 10m, 20m, and 34m run-up) there are 3204 potential vertical evacuation sites for the 34m scenario, 10,426 potential vertical evacuation sites for the 20m scenario, 2,046 potential vertical evacuation sites for 10m scenario, and 1643 potential vertical evacuation sites for the 5m scenario.

The analysis of the people movement over 24 hours has shown that there are discreet population distribution patterns depending on the time of the day. In the daytime, people are concentrated in the CBD for work and the other areas of the city are less populated, while in the nighttime the majority of the population is at home and distributed at the whole extent of the city. Finally, there are morning, noon and evening transit hours where great parts of the population are in transit, and outside buildings, at different locations in the city based on their transportation method. Concerning the capacity to accept people for vertical evacuation, the temporal population estimation and volume loss calculation indicate that on all four scenarios, the maximum total capacity to accept evacuees is achieved at 10am in the morning, with the 5m scenario sites allowing for 608,948 people to be accepted in the vertical evacuation sites, the 10 meter scenario allowing for 1,746,543 people to be accepted, the 20m scenario allowing for 5,764,030 people to be accepted, and the 34m scenario allowing for 1,865,315 people to be accepted. These numbers indicate that a majority of the city's population can be evacuated in potential evacuation sites that meet this study's criteria, within the tsunami flood zone of each scenario, greatly reducing the need for movement outside the tsunami flood. The approach further reveals, that this can be achieved by utilizing only existing buildings in the city without the need for additional construction. The 24h building population estimation method used allows for anticipating a building's population and capacity to accept evacuees during different times of the day allowing for temporal optimization of evacuation.

This study contributed in better understanding of how a moving population affects building population throughout the day and therefore the potential for vertical evacuation during different times of the day. The approach used in this research combines methods from different fields of Geography and GIS into a new approach that can be used in different locations that meet the data requirements, producing similar results that can be used by interested parties such as disaster planners, emergency managers and other Geographers in order to produce enhanced and optimized vertical evacuation plans.

Keywords: Building Population Estimation; GIS; Shizuoka; Tsunami; Vertical Evacuation

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Abbreviations

CBD	Central Business District
CSIS	Center for Spatial Information Science
DEM	Digital Elevation Model
GIS	Geographical Information System
GSI	Geospatial Information Authority of Japan
PTVA	Papathoma Tsunami Vulnerability Assessment

Chapter 1 Introduction

1.1 Background and problem statement

Natural disasters have been affecting populations around the world from ancient times. Natural disasters are the direct consequence of natural hazards, which are natural processes that become hazardous due to the presence of humans and their activities in areas that they occur (Keller, 2005). While geophysical events are implicated as triggers of natural disasters, the vulnerability of populations to natural hazards is due to social, economic and political processes that influence how people are affected by natural hazards and with different severities (Wisner, 2004).

There are different kinds of natural hazards, such as earthquakes, tsunamis, volcanic eruptions, floods, extreme weather phenomena etc, that are often interrelated. A tsunami is a wave or series of waves in a wave train, generated by the sudden vertical displacement of a column of water. This displacement can be a result of earthquake activity, volcanic activity, above water or marine landslides, asteroid impacts and meteorological phenomena. They can be generated in oceans, bays, lakes, rivers, and reservoirs (Bryant, 2008). It is a historical irony that the word tsunami originates in the Japanese language meaning harbor wave, as it was observed in historic times as a wave that destroys ports or harbors. On the 11th of March, 2011, the North-East coast of Japan suffered the most recent tsunami event that originated from a M 9.0 earthquake and resulted in approximately 15,856 deaths, 3,084 missing persons, and the injury of 6,025 others (National Police Agency of Japan, 2012).

While the 2011 Tohoku Earthquake and subsequent tsunami were unfortunate disasters, it proved to be a scientific opportunity for further studying tsunamis and their effects in human presence and activities. Among the lessons learned from the event was the fact that earthquakes of such magnitude result in very big tsunamis that can destroy human constructions from buildings to roads and bridges. Among the destroyed buildings discovered by fieldwork in the aftermath of the tsunami

are houses, offices and the Disaster Prevention building in Minami-Sanriku (Suppasri et al., 2012). Again, Minami-Sanriku is an unfortunate example as the tsunami brought complete destruction to buildings that were designated as vertical evacuation sites for tsunamis (S. Fraser et al., 2012). The field work literature after the Tohoku tsunami is very extensive, but most of it trends to the same conclusion that many evacuation sites were damaged or destroyed, not allowing for the safe evacuation of locals, causing injuries or even loss of life.

Clearly, while every Japanese coastal city has its evacuation plan, it becomes apparent that it might not always be sufficient or optimized in order for the majority of a coastal population to safely seek refuge in the event of Tsunami. Often times, construction standards of Japanese cities, while earthquake resistant, prove to be little resilient to tsunamis, increasing the vulnerability of locals in areas where tsunamis might occur (Voulgaris and Murayama, 2014).

This study will focus on the tsunami hazard in the South East Coast of Japan, as it is has happened in the past and is expected to reappear in the future originating by earthquakes in the Nankai Trough Subduction Zone which is known to generate earthquakes of M>8.0 in historic and older eras (Yoshioka and Hashimoto, 1989). In 2003, the Japanese government established that an M 9.0 earthquake is expected to occur in the Nankai Trough, resulting in a Tsunami with a maximum run-up of 20m. This scenario was revised after the 2011 Tohoku event, now expected to give a maximum run-up of 34m across 8 prefectures in South-East Japan.

Under these circumstances it becomes apparent that there is a need for further investigating whether the Southeast coastline of Japan is prepared to evacuate the local residents in the event of such a tsunami. Potential evacuation sites within the existing urban structure need to be identified spatially and under different tsunami scenarios. Moreover, they need to be evaluated as per their endurance in those tsunami scenarios, and investigated as to whether they are capable of accommodating the local population in the event of a tsunami.

1.2 Literature review

1.2.1 Earthquake and tsunami hazard from the Nankai Trough

From the Nankai Trough, the northern part of the Philippine Sea plate is subducted beneath Southwest Japan, resulting in the occurrence of great interplate earthquakes (Hori and Oike, 1999). During historical times, large earthquakes have occurred along the Nankai Trough with an average interval of about 120 years, with the most recent earthquakes being the M 8.0 1944 Tonankai earthquake and the M 8.1 1946 Nankaido earthquake (Yoshioka, 1990)(Figure 1-1). This kind of repeated mega-thrust earthquake activity implies that another great earthquake may occur in the future that would cause serious widespread damage in central to western Japan (Nakano et al., 2013).

It is a well established fact that tsunamis follow large interplate earthquakes when they occur underwater. The 1946 Nankaido earthquake was followed by a tsunami (Cummins, et al., 2002), but given the technology and scientific advancements of the time of the earthquake little is know about its run-up height. Similarly, in 1707 the Hoei Earthquake(Imai et al., 2010) and subsequent tsunami occurred in the Nankai Trough (Hyodo & Hori, 2013), with very limited indications of a run-up of 5 meters (Imai et al., 2010). Extending further in the past, beyond historical times, there are numerous tsunami deposits along the coastlines of southeast Japan that suggest a tsunami presence of at least 3000 years, with the shortest occurrence period being between 100 and 200 years (Komatsubara and Fujiwara, 2007)(Figure 1-2). The run-up from a mega thrust earthquake in the Nankai Trough can be indirectly inferred and anticipated by results from the numerous recent studies of the similar seismic zone that gave the 2011 Tohoku Earthquake and Tsunami. Following the M 9.0 Tohoku Earthquake the tsunami that happened reached very large run-up heights, with field studies indicating a minimum of 10 meters (Gusman & Tanioka, 2014), and a maximum run-up of 35 to 40 meters in Sendai (Goto et al., 2012; Lin, et al., 2012), with an estimated inland penetration reaching a maximum of 3 kilometers at different locations (Gusman & Tanioka, 2014). Based on the above findings, it becomes apparent that there is a Holocene and historical tsunami presence in the Nankai Trough that can potentially result to a catastrophic tsunami in the near future.

Figure 1-1 The Nankai Trough and a list of historic earthquakes in the area.

Source: Imai et al., 2010

Figure 1-2 Tsunami deposits in regions facing the Nankai Trough.

Source: Komatsubara and Fujiwara, 2007

1.2.2 The concept of vertical evacuation

In areas where high ground is not reachable, tsunami vertical evacuation strategies can be applied to minimize loss of life. Japan for example, already utilizes buildings, platform, artificial berms as vertical evacuation sites for tsunami refugees, and coastal communities in the United States and Sumatra are already planning their adoption (Wood et al., 2014).

The Federal Emergency Management Agency of the United States (FEMA, 2009) defines a vertical evacuation site as follows:

"A vertical evacuation refuge from tsunamis is a building or earthen mound that has sufficient height to elevate evacuees above the level of tsunami inundation, and is designed and constructed with the strength and resiliency needed to resist the effects of tsunami waves.''

In other words, tall buildings that are not flooded, or high elevation locations can be used as vertical evacuation sites (see buildings in Figures 1-3 and 1-4). Vertical evacuation differs to the horizontal evacuation not only in the direction of the population movement, but also to the fact that vertical evacuation in most cases involves evacuating within the hazard zone itself (González-Riancho et al., 2013).

A vertical evacuation plan utilizes such sites and is comprised of different components that must be available in order to ensure safe evacuation. According to Scheer et al., 2012, a vertical evacuation plan should include the following components:

- Digital Elevation Model (DEM)
- Population distribution map
- Road and major paths map
- Map of special places
- Hazardous and dangerous areas
- Map showing evacuation hindering particulars
- Expected wave height
- Expected time of arrival

- Currents' velocities map
- Inundation and safe areas map
- Possible amendments to vertical shelters

From the above list, the great majority of components are either readily available as datasets, or are calculated, enhanced or improved for the City of Shizuoka during the procedures of this study.

There is a series of previous studies on the matter of vertical evacuation. Among them, different approaches are utilized in order to approach vertical evacuation. As mentioned above some are meant to establish what a vertical evacuation plan should be. Jonientz-Trisler et al., 2005, present a framework of tsunami hazard identification by the local governments in the diverse areas of California, Hawaii and Oregon in the United States. Based on the identification of the tsunami hazard in each of those areas, they propose a system of construction codes, zoning and infrastructure, as well as vertical evacuation guidelines, that is to be delivered by the local governments to the local residents. Among these areas, only Hawaii is listed as possessing the appropriate guidelines for vertical evacuation, but their nature and method of establishment remain vague.

As described earlier, Scheer et al., 2012, present an extended description on what a vertical evacuation plan should be, and the important requirements of detailed population characteristics in the hazardous areas, as well as the attributes of sites that will be used for vertical evacuation. However, in their detailed description of their view on the framework of vertical evacuation, they have no case study to present and evaluate the applicability of their suggested method as a whole.

Shibayama et al., 2013, use multiple field observations after the 2011 Tohoku tsunami in order to suggest a new approach to how buildings can be used for vertical evacuation in Japan. Their approach is using the number of floors in buildings in order to determine whether they could be used for shelter by people who are evacuating vertically. They propose three vertical evacuation site categories, A, high terrain, B, buildings with 7 or more floors, and C, buildings with 4 or more floors. Each category is utilized differently based on the severity of the tsunami, and might have a certain risk when used for vertical evacuation. For example, buildings in category C might become

completely flooded if a severe tsunami affects the areas where they are located. This study indicates the importance of the building height and the number of floors in vertical evacuation, however, it does not consider the population located in the buildings within the proposed categories, or how it might change over different times of the day. Moreover, they do not present a selected area as a case study, in order to evaluate their method and investigate the number of sites that result by establishing their three categories.

There are, however, studies with on-site approaches that aim in utilizing vertical evacuation sites or planning for vertical evacuation in different locations. One such study utilizes mathematical modelling in order to determine the need for evacuation shelters in Cannon Beach, Oregon, United States (Park et al., 2012). In their study, they use mathematical algorithms in order to determine the optimal locations for vertical evacuation sites in their study area. However, their approach focuses only on the spatial location aspect and does not include the characteristics of the vertical evacuation sites themselves. Moreover, the proposed vertical evacuation site locations might not be at places where buildings exist and therefore additional constructions may be required in order to utilize these locations.

Other studies focus more in the evacuation procedure itself utilizing already designated evacuation sites. For example, Freire et al., 2013 suggest a method that combines tsunami travel times on shore, as well as a daytime and nighttime population estimation in order to finally recommend the potential need for vertical evacuation in Lisbon Metropolitan Area, Portugal. Their method is one of the few that distinguishes between daytime and nighttime populations, and even though it results in knowledge about what kind of vertical evacuation is needed in their study area, it provides little insight on how this can be applied using the buildings currently available in the city.

N. J. Wood & Schmidtlein, 2011, have a totally different approach, using terrain models and geomorphological characteristics in the Long Beach Peninsula, United States, in order to determine optimal paths of evacuating verticall outside the tsunami flood in higher grounds. This approach results in very detailed pathways that can be ranked based on their difficulty to follow, but provides

little information on where exactly should people shelter themselves once they have followed the proposed paths.

There is a category of studies in tsunami vertical evacuation that includes those that focus on the behavior of local residents during an evacuation event. Charnkol & Tanaboriboon, 2006, investigate and evaluate the behaviour of the local population in Phuket and Phang-nga, Thailand, in order to classify their response time and behaviour during a tsunami vertical evacuation. They then use the reuslts of their investigation in order to model optimized evacuation flows towards higher ground, away from the tsunami flood. Hokugo, 2013, investigates the evacuation paths followed by the locals in various areas affected by the 2011 tohoku tsunami, and how they were affected by the outbreaks of fires in the buildings that they evacuated to. In many cases people had to abandon buildings that were on fire and evacuate again to different buidlings in order to save themselves. This study not only analyzes the behavior of the locals during vertical evacuation, but also focuses on the shortcomings of vertival evacuation that can be faced during its implementation.

Other than Hokugo, 2013, which shows that there can be cases where vertical evacuation can be unsafe, there is a series of studies that focus on the shortcomings or successes of vertical evacuation in areas around the world. Dall'Osso & Dominey-Howes, 2010, interviewed 500 residents in Manly, Australia, in order to determine whether they find the current vertical evacuation plan, as it is presented in maps, understandable or not. In their findings, they determined that even though the majority of interviewees find the information available in the maps understandable, they have a lot of suggestions or issues that could affect vertical evacuation in different ways.

Lindell et al., 2015, interviewed 262 Samoans in the American Samoa, in order to evaluate their responses to the 2009 Samoan earthquake and tsunami. In their research they tried to determine what contributed the most to their decisions when vertically evacuating, among their knowledge and evacuation drill, instructions by the media, as well as face to face contact and phonecalls with others during the event. While they found that knowledge about the tsunami hazard and participation on

evacuation drills resulted in increased awareness concerning vertical evacuation procedures, this knowledge did not result in higher chances of successful vertical evacuation to higher ground.

While there is an apparent abundance of studies on tsunami evacuation, and specifically vertical evacuation, there is little research on incorporating additional evacuation sites in an area whose tsunami hazard has been underestimated, such as Shizuoka City. The extensive literature available, does not cover ways in which the current urban structure can be utilized in order to increase the number of evacuation sites in order to improve evacuation efficiency.

Figure 1-3 School designated as a tsunami vertical evacuation site.

Source: FEMA, 2009

Figure 1-4 Lighthouse designated as a tsunami vertical evacuation site.

Source: FEMA, 2009

1.2.3 Tsunami water depth vs Inundation Ratio

Most of the tsunami geographic researches, whether hazard, risk or vulnerability assessments, evacuation planning or otherwise, utilize tsunami flood maps in order to visualize the tsunami hazard. These flood maps can either be based in modelling, for example in the vulnerability assessment case of Oregon, USA (Dominey-Howes et al., 2009) where detailed tsunami modelling is used in order to visualize the tsunami hazard. Generally, however, tsunami flood mapping is used based on hypotheses or run-up levels of tsunamis of the past. Two such cases are the case of Alexandria, Egypt (Eckert et al., 2012) and Casablanca, Morroco (Omira et al., 2009). Other than the fact that both studies use tsunami flood maps based on previous tsunamis, there is a second similarity. In the case of Alexandria, one of the vulnerability components is the water depth at the location of each building. Logically, the higher the water depth, the more vulnerable a building is. The case of Casablanca, utilizes the same concept, but in reverse. The variable used is the height of the building, and as such, the higher a building the less vulnerable it is considered to tsunamis.

However, simply utilizing the water depth without any consideration to the building height might not provide meaningful results. Shallow waters can still affect short buildings, and deep waters might not affect very tall buildings. The same applies for the reverse approach where tall buildings can still be affected by very deep tsunami waters, and short buildings might be unaffected based on their location. It becomes apparent that safe vertical evacuation sites within a tsunami flood zone should be buildings that are not flooded or partially flooded based on certain criteria. For this reason, a more different variable must be used to determine how flooded or not these buildings are.

This variable is the inundation ratio, and its concept also stems from vulnerability assessments. The inundation ratio is basically the combination of building height and tsunami water depth, whose division results in the percentage that a certain building is flooded. As a vulnerability component it was introduced with the first application of the Papathoma Tsunami Vulnerability Assessment Model (PTVAM) (Papathoma & Dominey-howes, 2003). This model has been improved and is currently on its third version (Dall'Osso et al., 2010; Dall'Osso et al., 2009; Tarbotton et al., 2012), with the

inundation ratio being one of its major components. Moreover, the inundation ratio has been field tested and applied in different locations around the world such as the Chiba Prefecture, Japan (Voulgaris and Murayama, 2014)(Figure 1-5), the Maldives, after the 2004 Indian Ocean tsunami(Dominey-Howes & Papathoma, 2006), and Sydney, Australia (Dominey-howes & Dall'Osso, 2009).

Hence, the importance of the inundation ratio in determining the flooding extent, and the vulnerability of a building becomes apparent, especially when dealing with structures that will be used for tsunami evacuation. This study uses the inundation ratio as a core component, and as a main factor of identifying a potential evacuation site. The application of the inundation ratio and the procedure itself are explained in detail in Chapter 3.

Figure 1-5 Spatial distribution of the inundation ratio of buildings in Aihama, Chiba Prefecture, Japan, over a 10m run-up tsunami scenario.

Source: Voulgaris and Murayama, 2014

1.2.4 Building population estimation studies

When it comes to using buildings as potential evacuation sites, among the most important things to consider is the population that is inside each building. This is imperative information for disaster management, as knowing an estimate of a building's population allows for further investigation of how many more people can seek refuge in that building in order to save their lives from a hazard.

Lwin and Murayama (2009), introduce a GIS based building population estimation method, which utilizes two datasets that are available for the majority of regions in Japan and in many other locations around the world. This method uses building footprints, and population census meshes (census tracts) in order to estimate the population of each building footprint. In summary, the population of each census tract is divided in segments and assigned to each building footprint based on the surface of its footprint, or the size of its volume. The product of this method is a set of building footprints that now include the number of estimated people in them. This method is especially recommended by its authors for use in natural disaster prevention (Lwin and Murayama, 2009). The method was combined with a vulnerability assessment tool and gave useful results in estimating the population of vulnerable buildings in Aihama, Tateyama City, Chiba Prefecture (Voulgaris and Murayama, 2014). However, a useful tool this might be, it is not devoid of limitations. Perhaps the most important of them is the fact that it estimates the population at a certain time frame, depending on the kind of census data used as an input. For example, using a resident census results in what is known as a night time building population, as the majority of residents can be found in their houses only at night time. Using a worker census will result in the estimation of a daytime building population, as the majority of workers are found at their work place in the daytime.

This limitation led to the use and upgrade of Lwin and Murayama's (2009) method by Greger (2014). In a study of a different kind of disaster, terrorist attacks in Tokyo, Japan, Greger (2014) incorporated the temporal dimension in the building estimation population method by utilizing people flow data and building use data. In his study, he was able to estimate the variances of the populations in the buildings of Central Tokyo, and over the course of 24 hours of a day. By upgrading the method

to include the temporal dimension his terrorism vulnerability assessment was able to identify times of the day where certain locations were less or more vulnerable based on the presence or absence of population in the buildings located there.

As it will be explained in Chapter 4, this study will use the method by Lwin and Murayama (2009), as a basis, but will attempt a similar approach to Greger (2014) in order to estimate the variances in building population in Tateyama City.

1.3 Research purpose and objectives

In the previous sub-chapter, there was a presentation of extensive literature concerning vertical evacuation to tsunamis. It was made clear that there is an abundance of literature that defines the required attributes of vertical evacuation shelters in detail, indicating as the most important parameter the height, or floor number of these sites. Moreover, it was made clear that there is a need for a detailed hazard mapping of the tsunami hazard in the areas that can potentially be affected by tsunamis. However, the studies that suggest frameworks of vertical evacuation sites and procedures, lack the real world application and case studies that can provide an evaluation of their viability. There are limited to no investigations on the microscale level, of whether the vertical evacuation attributes that are set in these frameworks can be found in reality.

While on one hand there is a lack of a real life application of vertical evacuation attributes and criteria, there is an abundance of geographical approaches and tools that can be used towards this goal. The literature review presented two main approaches that allow for detailed building by building flooding and hourly population estimations that have robust results and previous applications in vulnerability studies.

Due to the above, this research implements these geographical tools and combines them for the first time into a methodology that aims in finding vertical evacuation sites that meet the attributes described in a plethora of framework studies, and it does so using the existing building stock in the study area of the Shizuoka Metropolitan Area, without the need for additional construction of vertical

evacuation sites. Moreover, by utilizing a 24 hour building population estimation model, this research covers the literature gap found in the majority of vertical evacuation studies that considers only the night time population in the hazardous areas, even though most of the framework studies indicate the need for detailed population analyses in vertical evacuation planning.

Therefore, the purpose of this research is to investigate the potential for vertical evacuation in the Shizuoka Metropolitan area. This will be accomplished by using Geographical Information Systems (GIS) in order to find potential vertical evacuation sites, and subsequently analyze their capacity to carry the local population under variable tsunami scenarios and different time zones of the day. The city of Shizuoka is selected due to its position relative to the tsunamigenic Nankai Trough (see Chapter 12.1) which places it in an area of high tsunami risk, as well as its centrality in Japanese Geography, in relation with its administrative infrastructure as capital of the Prefecture, as well as its road and rail infrastructure, as a central node of transportation connecting East and West Japan. Specifically, this research has the following objectives:

- Establishment of four tsunami scenarios. Using knowledge of past tsunamis in the area as well as the knowledge and experience obtained from the great Tohoku tsunami, four tsunami scenarios with variable severity are established, visualized and utilized for the city of Shizuoka. These four cases stem from current tsunami planning of the Japanese government as well as literature review of tsunamis that have happened in the past, resulting in two severe and two less severe scenarios.
- Identification of potential evacuation sites within the tsunami scenario flood zones. By considering all building of the urban structure of Shizuoka City, non flooded or partially flooded buildings will be identified and selected as potential evacuation sites in case of a tsunami event.
- Temporal building population estimation. Utilizing the person trip people flow data for the city of Shizuoka, the building population will be estimated for different times of the day in

order to approximate how many people are already in the potential sites, and how many more can be accepted during different hours of the day.

- To combine the research approaches of this study into a method applicable in different locations in Japan and around the world, where similar data sets are available.
- To disseminate the results of this research to academia, local governments and residents, in order to help improve evacuation planning and efficiency, potentially saving more lives during a tsunami event.

1.4 Research structure

The structure of this research is presented in Figure 1-6, and is described in three boxes. The topmost box includes the objectives of the study as described earlier, followed by the approaches and methods that were used in the main analysis of this research which finally led to the final box that contains the conclusions of the research.

The first part of this study focuses on the physical characteristics of the study area. Tsunami flood maps were made and used in order to determine the water depth at the location of each building. This was combined with building floor information in order to determine to which extent each building is flooded and how much of its volume is left to be utilized for vertical evacuation. The second part deals with the population characteristics, namely how many people can be found in each building and at different times of the day. Evacuation criteria are introduced per tsunami scenario and different levels of strictness are applied in the volume assigned in the people already inside each building and those that are going to be accepted for vertical evacuation. The results of this approach are grouped per scenario and their spatial distribution is visualized in a map.

Based on the results of the analyses and estimations conducted there is a series of conclusions concerning the overall potential for vertical evacuation per scenario severity and time of the day. It becomes apparent that the time that the tsunami occurs can result in increased or decreased potentials for vertical evacuation. Moreover, the severity of the tsunami in combination with the time can limit

the spatial availability of potential vertical evacuation sites available in each tsunami flood zone. The severe scenarios allow for vertical evacuation only in the center of the city, while the less severe ones offer multiple options on the full extent of their flood zones.

This thesis is structured in 6 chapters: (1) Introduction, (2) Study Area: The City of Shizuoka, (3) Exposure, inundation ratio and building volume loss, (4) Building population estimation over 24 hours of a day, (5) Estimating the potential for vertical evacuation, and (6) Conclusions.

Figure 1-6 Flow of the research.

Chapter 2 Study Area: The City of Shizuoka

2.1 Geographical Setting

The Shizuoka Prefecture is a prefecture located in the Honshu Island of Japan, covering an area of 7,779 square kilometers (Shizuoka Prefecture, 2014). It is a generally mountainous area, and the home of the world famous volcano, Mount Fuji. With its coastline, it faces the Pacific Ocean directly and therefore the Nankai Trough. Along its coastline, many rivers meet the sea, forming deltaic flat regions, and as such locations suitable for urban development. There are 23 cities in the Shizuoka Prefecture, with a total population of 3,774,471 people, making it the 10th most populated prefecture in Japan, following the Fukuoka Prefecture, and followed by the Ibaraki Prefecture (2010 Census, National Statistics Agency).

The capital city of the Shizuoka Prefecture is the city of Shizuoka (Figure 2-1), with a population of approximately 723,000 people (Shizuoka City, 2014). Shizuoka City is the second largest city in population within the prefecture, following Hamamatsu with population of approximately 780,000 people. The city is situated on the delta of a complex river system with many new and old canals flowing into the sea via its coastline. While the city is generally situated in very low elevation, within the city there is the geologic formation of the Udo Mountain, which is a protruding hill in the eastern part of the city. While this mountainous area is mostly unpopulated, the majority of the deltaic area is built up into an urban environment which is divided administratively into three wards: Aoi, Shimizu and Suruga.

The city of Shizuoka plays a very important role in the geography of not only the Shizuoka Prefecture, but the geography of Japan in general. As will be described in detail in the following sub-chapters, central highways, main arteries of the Shinkansen (bullet-train) rail lines that connect Western Japan with the East and vice versa, pass through Shizuoka City. Moreover, the majority of the administration buildings of the prefecture are located within the city. This setting constitutes a heavy geographical role, and makes it a critical node of many of Japan's transport networks. As such, any potential hazard to the city is a hazard for the prefecture, and in greater extent to Japan itself.

Given the fact that the city faces the Nankai Trough, and the hazard that is connected with this seismic zone, any tsunami affecting the area could have consequences extending beyond the city itself and possibly affecting the whole of Japan to a certain degree.

For the above reasons, the city of Shizuoka was selected to be the study area of this research. Various datasets were collected, and field work was conducted in order to assess the potential for vertical evacuation in the city's existing urban structure.

Figure 2-1 Location of the Shizuoka Prefecture, Shizuoka City and its three Wards, the Central Business District of Shizuoka city and the boundary of the Study Area.

2.2 Data collection

For the purposes of this study, as described in Chapter 1-2, various datasets were collected, combined, analyzed, visualized and presented. The majority of the data is in digital form, and in one way or another became part of a GIS database that was the source of any calculation, estimation or analysis performed. The majority of the digital data was readily available by various sources in Japan, the majority of which was of open access nature and is openly available in the public. The main data sources were the Geospatial Authority of Japan (GSI) which provided a lot of physical characteristics data, such as roads and the Digital Elevation Model (DEM), the National Statistics Agency of Japan, which has very detailed spatial census data, as well as detailed population statistics, the Center for Spatial Information Science (CSIS) of the University of Tokyo, which provided the Zenrin Zmap Town II and Telepoint data, the People Flow Data for Shizuoka, and finally, the Ministry of Land, Infrastructure, Transportation and Tourism, National Information Division, which provided the GIS data of the current designated evacuation sites for the Shizuoka Prefecture, including of course Shizuoka City.

With the digital data having the prime role in this study, during its course, many analyses and calculations were conducted using all these datasets. While the results were fruitful and led to the deduction of many useful conclusions, there was a need of validation of the analyses performed. For this reason, extensive field work was conducted in order to collect field data for two purposes: (a) to ground truth attributes of potential vertical evacuation buildings in selected sample areas in order to verify their endurance to tsunamis based on their characteristics, and (b) to validate the results of the temporal building population estimation method used (see Chapter 4), by comparing field observations and estimated values. Therefore, while the field work data were valuable, they played a more supportive role over the course of this research, connecting the digital with reality. Naturally, the field surveys conducted were not only limited to raw data gathering, but they also focused on familiarizing with the study area and getting an overview of the geographic setting of the region,

observing the local population and identifying other potential problems in case a tsunami event occurs.

Since every source provided different and multiple data, within Table 2-1 are contained all datasets that were collected, their sources, and the year that they were delivered, while Table 2-2 indicates the field survey methods and data collected during field surveys in Shizuoka.

Table 2-1 Data collected during the course of this study, including the time of issue or collection and their providing source.

Data Types	Year	Source
Physical Features		
Road Network	2013	Geospatial Authority of Japan
Rail Network	2013	Geospatial Authority of Japan
Buildings footprints with Floor Number	2008/2009	Zenrin Zmap Town II (CSIS)
Building Use	2014	Zenrin Telepoint Pack (CSIS)
Digital Elevation Model (5m)	2013	Geospatial Authority of Japan
Designated Evacuation Sites	2012	Ministry of Land, Infrastructure, Transportation and Tourism
Building Attributes	2015	Field Survey
Population Features		
500m Residential Census Mesh	2010	National Statistics Agency
500m Workforce Census Mesh	2010	National Statistics Agency
Population census and age structure	2010	National Statistics Agency
People flow for Shizuoka (Person Trip)	2001	CSIS
24h Building Population (2 Buildings)	2015	Field Survey
Other Data		
Shizuoka City Evacuation Plan Material (Pamplets, Booklets, Flyers etc)	2015	Field Survey/ Shizuoka City Municipal Office
Photographs of study area	2015	Field Survey

Table 2-2 Field survey data collection methods, data types and time frame of collection.

Data Types	Time Obtained	Method Obtained
Building Physical Features (749 Buildings)		
Construction Material	July 2015	On-Site Observation
Preservation Conditions	July 2015	On-Site Observation
Use	July 2015	On-Site Observation
Population Characteristics (2 Buildings)		
People Entering Over 24h	July 2015	On-Site Observation
People Exiting Over 24h	July 2015	On-Site Observation
Other Materials		
Study Area Photographs	July 2015	On-Site Photography
Interaction with Locals/ Interviews	July 2015	On-Site Communication with Locals

2.3 Urban structure of Shizuoka City

As mentioned in Chapter 1.3 one of the main objectives of this research is to use the existing urban structure in order to find potential vertical evacuation sites within it. In other words, there is a need to find buildings that are tall and durable enough to withstand tsunamis and shelter the locals during their evacuation. Moreover, utilizing the existing urban structure of the city means that this study is not focused on finding suitable locations to construct new evacuation sites, but rather, to set criteria and attributes that if met by the current buildings of the city, they are considered as potential sites for evacuation in the case of a tsunami. This study considers as urban structure of Shizuoka City the whole extent o its building stock, as well as the attributes of height (number of floors) and volume of each building.

In order to study, understand and visualize the urban structure of the city, two methods were utilized The first one is field surveys in order to familiarize with the setting and the city itself. However, the city is too extensive and vast for building by building investigations to be conducted on its whole. Therefore, digital data were used in order to capture the urban structure of Shizuoka city. The dataset that was utilized was the Zenrin Zmap Town II of 2008/2009 as it was provided by CSIS (Figure 2-2). This dataset contains in shapefile form the majority of the building footprints of the city. Moreover, for about a third of those footprints, floor number information is included. At first glance this might seem like a limitation of the data, however careful observation of the data overlaid on satellite imagery reveals that the majority of tall buildings in Shizuoka are included in the Zenrin Zmap Town II dataset.

There are 99,140 buildings in Shizuoka. Out of them the tallest ones are situated in the Central Business District (CBD) of the city in the northern Aoi Ward (Figures 2-2), where tall office, commercial and multi apartment buildings are situated. The CBD also hosts the Shizuoka Central train station which is a central node in Japan's transportation via rail. Outside the CBD, there are tall residences spread all over the city, but tall office and commercial buildings are mostly found in

Shimizu (Figure 2-4, 2-5), of the the Shimizu ward, surrounding the train station of Shimizu. Shimizu also hosts the city's only port which constitutes it an important node of naval transportation.

In order to delineate the CBD of the city of Shizuoka, the building height itself was not a sufficient dataset. While in many cases it coincides that the CBD of a city is the area with the tallest buildings, it does not necessarily mean that wherever there are tall buildings it is also the CBD. For example, in Shizuoka City, other than the center, there are numerous tall buildings in the area of Shimizu, and to a fewer extent in Suruga. These two areas are very far from the center and have nothing to do with the CBD, in fact, tall buildings in these areas are usually of residential use. To delineate the CBD, the Telepoint Pack dataset of February 2014 was used. This dataset contains phonebook information in point format, and from it, the use of buildings can be derived wherever the points overlap buildings. As such, this dataset allows to distinguish between building use categories. The area that was finally delineated as the CBD of Shizuoka was the area that contains the blocks in the center of the city that are of purely commercial use. This distinction was very discreet and obvious from the data. The blocks outside the CBD contain numerous residential buildings and therefore were not included in the CBD. It became obvious from this process, that the CBD is a purely commercial or office building use area, but also that it contains the buildings with the highest numbers of floors.

Figure 2-2 The Zenrin Zmap Town II 2008/2009 dataset visualized as per the floor number. In the sotuhwest of the map the part of the CBD is seen containing the tallest buildings in Shizuoka.

Data source: CSIS. Basemap Source: Bing, 2014

Figure 2-3 Photograph of an area in the CBD of Shizuoka City.

Figure 2-4 Photograph of the center of Shimizu, as seen from the inside of the Shimizu train station.

Figure 2-5 Office and residence buildings in the area around the center of Shimizu.

2.4 Transportation networks

As mentioned earlier, the city of Shizuoka plays an important role in the transportation network of not only the Shizuoka Prefecture but also Japan. The road network of Shizuoka goes through the city in the shape of a net, with roads intersecting the urban landscape parallel and vertical to the coastline (Figure 2-6). There are 5 main national arteries crossing the city: National Routes 1 and 52 intersect the city east to west and through its central area, National Routes 149 and 150 also intersect east to west, but follow the coastline in the very south of the city, and National Route 362 again east to west, passes through the city on the north of its CBD. The Tomei and Shin Tomei expressways also pass through Shizuoka, but only through a very small built up area on the very south of the city.

The nature of the road network of Shizuoka is very important when it comes to tsunamis. The first reason can be the same for any kind of disaster that could impair a transportation network, and it is infrastructure disutility. Given the fact that there are 7 highways going through the city many of them connecting areas of Western Japan with the East, can deny important transportation in case a tsunami happens. This can affect not only long term evacuation after a tsunami, but also emergency response and transportation to other areas by inhibiting access in the aftermath of a tsunami event.

The second reason that the road network is important is of more relevance to this study. There is a plethora of main road arteries crossing the city from south to north and from the coastline to the inland. This is very important as roads provide pathways for tsunami flood waters to penetrate inland. While tsunami scenarios usually consider that an urban coastal area is flooded uniformly, this might not always be the case, but higher elevations can be reached by tsunami waters affecting the city in smaller areas following the roads uphill.

Finally, the nature of the highways that cross the city can be an inhibitor to evacuating to higher ground, as many of these highways are built on artificial slopes or cross through fenced areas or overpasses that cannot be crossed by pedestrians. The east-west crossing of all the major highways essentially divides the city into strips that in many areas of their length cannot have blocked passages that make crossing impossible. As such, any evacuation plan must consider this kind of obstacles that

are presented by the inevitable need for transportation route. While this study focuses on the evacuation sites themselves, this fact cannot be overlooked, as access to those evacuation sites can be denied due to the construction characteristics of the road network.

The rail network in Shizuoka city has similar characteristics to the main road arteries described above. While it is naturally not as extensive, there are 3 companies operating rail in the city. The first is the Central Japan Railway Company, with the Tokaido Bullet Train stopping at the Central Shizuoka Station only, and Tokaido Line stopping in 10 stations within the city, including the Shizuoka Central Station and Shimizu. The Shizuoka Railway Company operates with 10 stations in the Shizuoka Shimizu line, and finally the non commercial Oikawa Rail Company transports workers and materials, with two stations operating in the city of Shizuoka.

The rail lines intersect with the city in east- west direction and through the central part of Shizuoka (Figure 2-6). While the Central Japan Railway line is mostly straight from east to west, the Shizuoka Railway Company line deviates to the south in the western area to service Shimizu. Other than this part, the tracks generally follow the same line without any deviations or other kinds of unusual patterns.

In a similar fashion to the road network, the rail network plays an important role to Japan's transportation. If a tsunami event were to disable the rail system in Shizuoka, the loss of the Shizuoka-Shimizu line would perhaps not be as important, as emergency transport is not usually conducted by train. However, the loss of the Tokaido line would be of crucial importance, as it essentially would cut rail transport between East and West Japan in half, by disabling the Bullet Train and the lesser speed train transport.

Again, in great similarity to the road network the rail network divides the city in two halves by an inaccessible barrier that can only be crossed through train stations, bridges or tunnels across its length. While the rail network has a single line crossing through the city, it is far more difficult to cross than the road network as in its whole length it is inaccessible to pedestrians via fencing or other means, for obvious safety reasons. This means that in case of a tsunami people evacuating to the north

to reach either vertical evacuation sites or higher ground could find themselves unable to cross the train lines. Moreover, the parts that the train lines can be crossed from are bridges and tunnels that might have been damaged by the earthquake that precedes the tsunami itself, further limiting the ability to cross the rail lines by evacuees. Especially in the area of Shimizu, where the Shizuoka-Shimizu line splits southward from the Tokaido line, there is a cluster of the city surrounded by rail to north and south limiting access to the outside in this way.

It becomes apparent both from the urban structure of the city as well as the transportation network patterns that evacuation vertically is a very viable option that limits the need for long distance movement when evacuating from a tsunami. If there is a vertical evacuation site close by, local residents do not have to worry about overcoming natural and artificial barriers such as the ones presented by the transport networks, and can safely evacuate to a tall, durable building in their proximity to save themselves from an impeding tsunami.

Figure 2-6 Transportation networks of Shizuoka City.

2.5 Tsunami run-up scenarios

In every geographic tsunami research conducted it is important to establish a tsunami scenario that will be the basis of the research. In this study it will be attempted to utilize four tsunami scenarios of variable severity in order to cover not only the worst case but also scenarios of lesser severity.

The scenarios that were considered in for this study were initially two, and were directly adopted from the Central Japanese Government. In 2003 the Japanese Government established a tsunami scenario for a tsunami originating from a M 9.0 earthquake in the Nankai Trough, which would have a maximum run-up of 20m, affecting 8 prefectures, including the Shizuoka Prefecture. However, after the events of the Tohoku Earthquake and the run-up heights observed in the tsunami that followed it, in 2013 the Japanese Government's scenario was reviewed and updated to a tsunami of maximum run-up of 34m instead.

At this point it is important to realize what these numbers mean. The run-up of the tsunami is very different from the wave height of the tsunami. The run-up is the maximum altitude the tsunami flood waters reach when they flood the coast, and it is often two times the tsunami wave height as it reaches the coastline or even higher (Bryant, 2008). This means that a 20m or 34m run up tsunami can flood a very extensive area if it is flat, such as the deltaic plain of Shizuoka city.

In order to visualize these two scenarios a single dataset and GIS software was required. For the run-up of a tsunami to be calculated, it needs to be subtracted from the elevation of the area that is investigated. For this reason, a 5m DEM issued by the Geospatial Authority of Japan was utilized. The run-up calculation was conducted as follows:

Run-up – Elevation = Tsunami Water Depth (2-1)

Equation 2-1 was input in the GIS platform and used the 5m DEM for the calculation. Figures 2-7 and 2-8 show the results of the 34m and 20m tsunami run-up calculation visualized in discreet water depths. The results of the mapping are of great interest as the 34m run-up scenario effectively covers

the majority of the built up area of the city. While the 20m case is less severe, it still manages to affect a great part of the city as well. Both scenarios, reach inland even all the way the north where the CBD is located, and approaching the coast, the depths of the tsunami flood zones are enough to cover even 10 floor buildings.

These findings make the importance of vertical evacuation even more apparent. In such extensive flood zones, evacuation outside the tsunami waters can be impossible. It would be far more prudent, convenient and less time consuming to evacuate to a tall, resilient building with the flood zone in order to reach safety. However, the water depths of both the scenarios are so immense that they leave very few buildings not flooded. Though extreme these run-ups might be, they were very recently observed in Sendai, after the Tohoku earthquake and tsunami, where run-up heights were recorded even at 40m of elevation (Goto et al., 2012). Regardless of this, it was deemed necessary to investigate less severe scenarios in order to cover more possible cases and to introduce a more variable approach method that does not only consider one worst case, but four different cases with corresponding severities.

As a medium severity scenario this study considers a 10m run-up tsunami. The height of this run-up has been used in previous studies such as Voulgaris and Murayama (2014), where the tsunami generating earthquake is of a lesser magnitude of 8. Based on the Imamura-Iida tsunami magnitude scale (Bryant, 2008) such an earthquake can have a maximum run-up of 10m. In the case of Shizuoka, such a tsunami cannot only originate from the Nankai Trough, but tsunamigenic earthquakes of this magnitude occur along the Sagami Trough to the north east of Shizuoka and to the south of the Chiba Prefecture (Fujiwara & Kamataki, 2007; Komatsubara & Fujiwara, 2007; Nishizawa et al., 1996; Ogawa et al., 1989).

The final and lowest severity scenario is based on the historic 1707 Hoei earthquake. This earthquake is estimated to have had a magnitude of 8.4 (Sugimoto et al., 2003) originating from the Nankai Trough, and to have cause a tsunami that had a maximum run-up of 5 meters (Imai et al., 2010). This scenario is considered to be the weakest of the four, and while it would be possible to

examine scenarios of lesser severity, their impact on the city would not be of such significance to require the establishing of vertical evacuation sites within the flood zone, as the flood zone of a 1 meter or 2 meter run-up tsunami would be very limited.

In the same way as the 34m and the 20m run-up scenarios the 10m and 5m ones were calculated by subtracting the maximum run-up from the DEM using GIS. The results of this calculation can be seen in Figures 2-9 and 2-10 where the 10m and 5m scenarios are visualized respectively. While the 10m run-up scenario is much less severe than the 34m or 20m ones, it still has a very extensive flood zone to the southern coastline, but it manages a greater inland penetration in the north-east area. This is due to the fact that the tsunami waters entering from the area of Shimizu can follow the rivers upwards in a path that has very little slope and elevation, and hence can travel greater distances inland. While the situation is similar in the case of the 5m run-up scenario, the tsunami flood is not as extensive, being limited to the area of Suruga, and Shimizu, and while the flood still follows the river, reaching a 5m elevation is not as intrusive as the 10m one.

All four scenarios are important in their own way, and all of them are deemed necessary to be investigated when it comes to the potential of vertical evacuation. While the bigger scenarios are very extensive, even overwhelming, they are far from being unrealistic and it is imperative to study them as they might even be the most probable. The lesser scenarios are expected to provide a greater potential for vertical evacuation and will provide a more versatile environment with more options for evacuation within the flood zone.

Figure 2-7 34m run-up tsunami inundation scenario in the city of Shizuoka.

Figure 2-8 20m run-up tsunami inundation scenario in the city of Shizuoka.

Figure 2-9 10m run-up tsunami inundation scenario in the city of Shizuoka.

Figure 2-10 5m run-up tsunami inundation scenario in the city of Shizuoka.

2.6 Current evacuation sites and evacuation plan in Shizuoka City

The current evacuation sites and evacuation plan for the city of Shizuoka is a mixed situation that is within the jurisdiction of two authorities. First, the city of Shizuoka has a fully developed evacuation plan (Shizuoka City Municipal Office, 2015), in digital and printed form, advising the locals on what actions they must take and where to evacuate in the event of a tsunami. Other than that, the Ministry of Land Infrastructure, Transportation and Tourism, via its Division of National Information (2012) provides in digital form (GIS shapefiles), a dataset with the evacuation sites for all types of disasters, and for the whole of Japan. Among these, the public can have access to whichever city or area they want, and inspect the data themselves, or in the case of this study, perform certain analyses to support the claim that there is a need for more vertical evacuation sites. The following sub chapters are going to discuss the two datasets and evacuation procedures for Shizuoka City.

2.6.1 Analyzing the current evacuation sites with the use of GIS

As mentioned above, the GIS dataset is provided by the Ministry of Land, Infrastructure, Transportation and Tourism, Division of National Information (2012). The dataset comes in the point format, so each evacuation site is represented by a point. Figure 2-11 shows a map with the evacuation sites of Shizuoka City, overlaid on a Bing basemap. In this figure, it can be seen that there are evacuation sites all over the built up area of the city, but many of them are located to the north of the city in the mountainous areas, and away from the urban environment. As this study is concerned with evacuation sites within the city and within the tsunami flood zone, the evacuation sites outside the city will not be considered, as they are not useful for immediate tsunami evacuation.

The evacuation sites located within the city can be seen in Figure 2-12. From the database information that comes with each evacuation site, they can be classified per type, capacity or any other attribute that is included. The first problem that can be found in this information is that even though there is a field about the type of disaster that these evacuation sites are supposed to be for,

none of the sites is characterized for any specific disaster. This means that all the evacuation sites are theoretically for every kind of disaster. This leads to the next problem, which can again be seen in Figure 2-13. While many of the evacuation sites are of course buildings, the rest of them are flat open areas, such as hills, parks, etc. This means that for tsunamis, such evacuation sites are essentially a poor choice, as even the slightest of water renders them useless for safe evacuation.

Returning to the evacuation sites that are buildings, the dataset indicates that the great majority of them are either schools, or some other kind of public building. This means that they are limited to a certain kind of building use, and that not all the buildings of the city were considered in the selection of evacuation sites. Moreover, overlaying those buildings on the 34m tsunami scenario shows that many of these buildings an be found in very deep waters should such a tsunami occur. There is a total of 303 building evacuation sites in within the city of Shizuoka. For the 34m tsunami scenario 258 of them will be touched by water, and only 45 will remain unaffected. Moreover, the waters that these buildings will be in can be very deep. Table 2-3 shows the distribution of these evacuation sites based on their location in each tsunami scenario run-up. In the more severe cases of 34m and 20m, 258 and 200 sites respectively are affected by the tsunami waters, and in the case of the 10m and 5m run up scenarios 108 and 57 sites respectively are affected. As a result, it is expected that in the event different tsunami scenarios, many of the currently designated evacuation sites might become completely flooded, being useless to local residents who are evacuating.

The final parameter of the currently designated vertical evacuation sites that is going to be examined is their capacity. Of course, open space evacuation sites have the capacity to hold large numbers of people, but as established above, these are unsuitable for tsunami evacuation and are not considered. Even more so, when they have not a specific amount of people designated as their capacity in the dataset. Figure 2-12 shows the spatial distribution of the evacuation sites, visualized by their capacity. Table 2-4 shows the capacity statistics of the evacuation sites within the city. For some unknown reason, in the dataset there is an evacuation site with a capacity of 16, which, if it is not an error, is rather curious for an evacuation site. The largest evacuation is able to hold 2908

people. This is a rather big number, and it might be pushed beyond its limit in the event of such a huge emergency. On average, the capacity of the evacuation sites is 582 people which is a large number and can suffice for any evacuation site, provided that the number of sites is large enough.

And this is where the main problem with the currently designated evacuation sites lies. The total capacity of evacuation sites that are buildings and not open flat areas is for 111,897 people. Considering that the population of Shizuoka is approximately 723,000 people (2010 Census, National Statistics Agency), the capacity of the evacuation sites within the city is not enough to fit all of the residents of Shizuoka, not even half, only approximately 15% of the people of Shizuoka can fit into these evacuation sites. And that is without considering how many of them might get impaired, damaged, or destroyed by a tsunami.

It becomes apparent that the assumption of this study that there is a need for more vertical evacuation sites it is sound. Moreover, there is an apparent need to consider every building available for evacuation, and not a certain type as the currently designated evacuation sites which are either schools or public buildings. As will be shown in Chapter 3, and subsequently in Chapter 5, considering every building in the city of Shizuoka results in vertical evacuation site options that greatly exceed in numbers the ones that are currently available, and with far larger capacities to support evacuating people.

Figure 2-11 Current designated evacuation sites for the city of Shizuoka.

Source: Ministry of Land Infrastructure, Transportation and Tourism, 2012

Figure 2-12 Spatial distribution of evacuation sites within the city of Shizuoka over a 34m tsunami inundation scenario, classified per their capacity. The flat surface type has no maximum capacity.

Source: Ministry of Land, Infrastructure Transportation and Tourism, 2012

Table 2-3 Currently designated evacuation sites and their location in each tsunami scenario.

Scenario run-up	34m	20m	10m	5m
In tsunami flood zone	258	200	108	57
Dry	45	103	195	276

Source: Ministry of Land, Infrastructure, Transportation and Tourism, 2012

Table 2-4 Capacity statistics of currently designated evacuation sites in Shizuoka City.

Minimum Capacity	16
Maximum Capacity	2908
Average Capacity	582
Total Capacity of all sites	111,897
Shizuoka City Population	723,000

Source: Ministry of Land, Infrastructure, Transportation and Tourism, 2012

2.6.2 The Shizuoka City Municipal Office tsunami evacuation plan

The data presented in the previous sub chapter deal with the evacuation sites themselves, for example their kind, their capacity etc. The Shizuoka City Municipal Office (2015) has issued an extensive evacuation plan that is available to all local residents, or whoever else might be interested in such information. The ways that the information of the evacuation plan are disseminated are two: digital and analog.

When it comes to the analog distribution of material, it can be found in the Municipal Office itself, but also in many places around the city such as stores, restaurants, bank offices etc. The material comes in the form of pamphlets or posters that an interested individual can study and gain the information they require. These pamphlets illustrate the evacuation procedures should a tsunami happen, informing the reader that after an earthquake happens, the evacuation sites are opened within 5 minutes and the residents should seek refuge immediately should they hear the tsunami siren sound. Another kind of pamphlet shows a map of the Shimizu area displaying vertical evacuation sites over a 5m run-up scenario. The sites are various buildings, not just public buildings, including shopping centers etc. Finally, the third kind of pamphlet is also a map, but this time instead the inundation scenario of 5 meters is not visualized per its water depth, rather, it is visualized per the travel time of the tsunami water inland, classified in time frames of 0-10 minutes, 10-15 minutes, and 15 minutes or more. In the same map, one can find the same vertical evacuation sites, this time accompanied by arrows displaying the general direction that evacuees should follow in order to reach them.

The digital material provided by the Shizuoka City Municipal Office is essentially the same kind of information as the analog. All the above mentioned pamphlets and maps can be found in digital form at the Municipal Office's web page and can be searched by location of the city, downloaded and printed by the individuals that access the page. However, other than this material, the Shizuoka City Municipal Office offers an online Web GIS platform with information for all three kinds of natural disasters that affect the city: earthquakes, tsunamis and floods. In this Web GIS platform, a user can visualize the 5m tsunami scenario as per its water depth or travel time on shore, or view the designated

vertical evacuation sites for tsunamis, or any other of the two disasters. Moreover, evacuation directions are displayed with arrows in a similar manner as the analog pamphlets and maps described earlier. Unfortunately, these datasets are not available for download and analysis and can only be used within the limited parameters of the closed Web GIS platform.

When it comes to the Shizuoka City evacuation plan for tsunamis extensive work seems to have been done in order to provide both digital and analog information materials to the locals. While the evacuation instructions are clear and there are very detailed maps for every location, certain shortcomings of the evacuation plan can be identified by studying the provided material. The first one is that the vertical evacuation sites, when compared to the ones of the Ministry of Land, Infrastructure, Transportation and Tourism, include many more building use types other than just public buildings and schools. However, there is little transparency as to what criteria were used upon choosing these buildings. It appears as though there is only consideration on the building height, regardless of other parameters such as water depth of the tsunami. This is especially important, as the majority of those vertical evacuation sites seems to be within the 5m scenario flood zone. It is not in the material provided whether these buildings are partially flooded or not.

Moreover, it is questionable why there is only a 5m inundation scenario considered. The Japanese central government has issued scenarios with a maximum run up reaching even 34 m in height, a case of which would render the 5m evacuation sites inaccessible or potentially hazardous as they could be flooder and even destroyed. The lack of consideration of other scenarios even if they are not as severe is a shortcoming of the evacuation plan that points to a need for investigating other inundation scenarios if a better evacuation efficiency is to be achieved.

The last issue that is identified with the evacuation plan is the evacuation procedure itself. While the instructions are perfectly clear about what to do in case of a tsunami, where to go is portrayed in the form of abstract arrows to the above mentioned vertical evacuation sites. No road names or somehow tested or verified routes are suggested, instead merely generalized direction indicators to safe buildings. That fact demonstrates the need for a more precise and tested evacuation route

planning, with identifiable landmarks and routes that can be studied, memorized and utilized efficiently in times of need.

The above overview of the Shizuoka City Municipal Office tsunami evacuation plan is a strong indicator that there is a need to incorporate multiple tsunami inundation scenarios when researching the potential for vertical evacuation in the city of Shizuoka. While the plan seems to be taking many steps in the right direction of ensuring the safe evacuation of local residents, there is a series of shortcomings that demonstrate the need for research on more vertical evacuation sites and in variable tsunami scenarios.

2.7 Demographics of the city of Shizuoka

According to the 2010 national census (2010, National Statistics Agency), the city of Shizuoka has approximately 723,000 residents. The latest detailed census for the city is provided by the Shizuoka City Municipal office for September 2015, and it has a value of 713,000 residents in Shizuoka City, including foreigners. The United Nations Statistics Division (UNDATA, 2015) offers yearly information about the population of almost every city in the world. From 2003 till 2005, there was a small drop in population of about 2000 people, but from 2005 till 2010 the population increased by about 16,000 people, which for a city of 700,000 residents is a big gain. Figure 2-13 shows the current population per Ward in Shizuoka City. The Aoi Ward is the most populated ward of the three, with 256,000 residents, followed by the Shimizu Ward with 243,000 residents and the Suruga Ward with 211,000 residents. All three wards are almost the same in population, and while Suruga is the least populated, it is not falling back by great extends compared to the other two wards.

The most detailed information about Gender distribution and age groups is provided by the Shizuoka City Municipal Office (2015). Concerning the population distribution by gender, the female residents of Shizuoka City being about 20,000 more than the male residents. By utilizing the distribution of the population by age groups, it is possible to construct the population pyramid of the city. Figure 2-14 displays the population pyramid of Shizuoka City and as such the distribution of

population per age group. The largest age groups in Shizuoka City are the 40-44 age group and the 65-69 age group. The majority of the population belongs to ages of 35 and up, while the younger ages groups have far less people than the rest. There is also a great concentration of population in the age groups of 75 and up, especially in the females where there is a great chunk of population belonging to the group of 85 and up. This introduces a situation where a great portion of the population is elderly people, and hence can be considered belonging into sensitive age groups. These groups can have an increased difficulty when it comes to evacuating from tsunamis as their mobility is not as high as younger ages, and may burdened by other health conditions, or found in hospitals etc. While this is not the rule for everyone in the city, having a big portion of the population in sensitive age groups requires an evacuation plan that minimizes the travel time and distance to a vertical evacuation site, so that even sensitive age groups can evacuate efficiently.

Figure 2-13 Population distribution by ward, for the city of Shizuoka.

Source: Shizuoka City Municipal Office, 2015

Figure 2-14 Population pyramid of the city of Shizuoka.

Source: Shizuoka City Municipal Office, 2015

While the above statistics describe the characteristics of the population, in a geographical study such as this, the spatial characteristics of the population are of equal importance. The 2010 census (2010, National Statistics Agency) includes two datasets that show the spatial distribution of the population in Shizuoka City. Both datasets come in mesh form, with a resolution of 500m. In each 500m cell the first dataset offers resident information, and the second dataset offers workforce information (Figures 2-15, 2-16).

Figure 2-15 shows the residents mesh and how it is distributed spatially. In accordance with the statistics, the population in distributed among the three wards of Aoi, Shimizu and Suruga. Moreover, the city is populated somewhat uniformly in all its extent, with pockets of population concentrated in the centers of each ward, and especially around the CBD of the city. The information in this dataset is important as it highlights the population heavy areas in times where the majority of the population is expected to be at home. These are evening and night time hours, where everyone has returned from work or school or has finished the daily chores.

In Figure 2-16, one can see the spatial distribution of the workers in Shizuoka City. In this case the population is not as evenly distributed. In fact, the majority of workers are gathered in the CBD of the city, with a few small clusters in the center of Shimizu. This means that during the daytime, a great portion of the population moves towards the CBD and concentrates in that area during working hours.

The contrast between the daytime and night time indicates the need for a detailed and extensive population estimation that is distinct between times of the day so that the vertical evacuation sites can be found and may vary between times of a day.

Figure 2-15 500m residents population mesh for the city of Shizuoka.

Source: National Statistics Agency, 2010

Figure 2-16 500m workers population mesh for the city of Shizuoka.

Source: National Statistics Agency, 2010

Chapter 3 Exposure, Inundation Ratio and Building Volume Loss

This chapter will present the procedures followed in order to calculate the inundation ratio of buildings with floor number data in the city of Shizuoka. The calculation was conducted for all four tsunami scenarios and was based on two components: building height and water depth.

3.1 Calculation Assumptions

Due to the nature of the data available, there were two assumptions that were required to be made in order to calculate the inundation ratio. The first one deals with the height of each building floor. Building height data are not widespread and the areas that they might cover are not as extensive as Shizuoka City in its whole. For instance, one way to capture building heights is conducting field surveys, but in order to cover a whole city in its entirety, the time and monetary resources required would be forbidding. Another way to capture the building heights is by utilizing high resolution LIDAR data which come in mesh form and every cell of the mesh contains height information, which can be processed and refined via GIS, finally obtaining building height information for a certain area. However, obtaining such data is very costly, but even then, the area they cover is limited, and not extensive enough to cover the city.

Therefore, the height of the buildings had to be inferred indirectly. For this purpose, the Zenrin Zmap Town II dataset of 2008/2009 was utilized. As described in Chapter 2, this dataset contains floor number information for about one third of the buildings in Shizuoka City. As such, it is assumed that every floor has a height of 3 meters. Therefore, by multiplying the floor number of each footprint by three, the building height is estimated indirectly, for all buildings that have floor number information.

The second assumption necessary for calculating the inundation has to do with the tsunami flood water depth. While an exact tsunami flood model is not available for the study area, it is possible to visualize the maximum run-ups and study a tsunami scenario by using GIS to calculate water depths based on the scenario run up and the DEM (Chapter 2-5). While it is possible to estimate the

average water depth under each building, it is important to consider that the tsunami flood waters do not have a stable surface and might have complex patterns, waves etc. For this reason, every building's water depth is assumed to be submerged at the maximum water depth at its location, as this is a worst case scenario investigation. For example, if a building is between water depths of 9 and 10 meters, its water depth is assumed to be 10. This is due to the fact that even if the tsunami flood reaches the height of 10 at the location of a building for a very brief period of time, this still means that the building is unusable up to 10 meters, even if the waters recede slightly. This calculation will be explained in following sub-chapters.

3.2 Building height validation

As mentioned earlier, the building height for buildings in Shizuoka City was estimated by assuming that each floor of a building is 3m high and thus the building height was derived by multiplying its floor numbers by 3. This assumption was critical in the following steps of this study, as it is the basis for every calculation and estimation conducted from this point and onward. Therefore, it became necessary to test the assumption with real life data, and to validate it with such observations.

For this reason, a field survey was conducted, surveying 100 buildings in the city of Shizuoka and measuring their height using a portable laser height metering device. Out of the 100 buildings, 50 were measured in the area of the CBD in the Aoi ward and 50 were measured in the central area of Shimizu. Out of these buildings 40 were residences, and 60 were workplaces, such as offices, commercial buildings and two shopping malls. The focus on the non residential buildings was due to the fact that buildings of this category usually show variations in their floor height, as will be described later.

For the 40 measured residences, the average floor height was found to be at 2.95 meters, which is almost the same as the assumption that was used. There were almost no residences that had a floor height that was above 3 meters.

For the 60 workplaces the average floor number was found to be at 3.44 meters. This is not a great deviation from the assumption, but it is still a deviation and can be explained by two situations observed in the field. The first, is that shopping malls have very high floors, reaching up to even 6 meters, pulling the average to higher values. However, the shopping malls are very scarce, only 2 or 3 per city and this deviation can be overlooked. The second situation is that some buildings have lobbies in their first and second floors that are higher, and then the rest of their floors have 3 meters of height. This also is a factor that cannot be modelled or anticipated when performing estimations and calculations with thousands of buildings. Without including these kind of buildings, the majority of workplaces had an average height of 3.2 meters which again approximates the assumption of 3 meters per floor to a satisfactory extent.

Table 3.1 displays the results of the field measured buildings in the two locations of Shizuoka city. In these results, the very close approximation of the assumption to real life measurements becomes obvious. There is also no observable difference between the areas of Shimizu and the city center, even though Shimizu has much less tall buildings than the city center.

As such, it was observed in the field that the majority of buildings have floor heights that are approximately 3 meters, but there are a few exceptions that have higher values. For the purposes of this study, the assumption of 3 meters per floor was observed to be sound. The results of the field survey are summarized in Table 3-1, and a sample of the field surveyed buildings in the area of Shimizu can be seen in Figure 3-1.

Table 3-1 Field measured building heights

	Residences		**Workplaces**	
	City Center	Shimizu	City Center	Shimizu
Count	20	20	30	30
Average Height	2.94	2.96	3.55	3.34
Total average height	2.95		3.44	

Figure 3-1 Sample areas of field surveyed buildings in a) Shizuoka City Center, and b) Shimizu.

3.3 Building exposure

Exposure refers to the water depth of the tsunami flood at the location of a building (S. A. Fraser et al., 2014; Sato & Sawai, 2014; Tarbotton et al., 2012). In order to calculate the exposure of every building in a tsunami scenario certain GIS procedures were followed.

In order to ensure that the maximum water depth that affects every building is assigned to each footprint, spatial selection was utilized. Each tsunami scenario was divided in 1 meter intervals. Each 1-meter interval was assigned its maximum possible value, for example the zone between 0-1 meter water depth was assigned a value of 1, the zone between 1-2 was assigned the value of 2 and so on. This procedure makes sure that all buildings that are between variable water depths are going to receive the maximum value of water depth at their location.

In order to assign the water depth value of to the building footprints, each water depth zone is selected using GIS. For example, all water depth zones of 10 meters can be selected. Then, the GIS software can do a spatial selection of all the buildings that are located in zones where the maximum water depth is 10. This value is then assigned to the attribute table of the building footprints, for all buildings that are within this zone.

Sometimes, a building is located between two different zones, for example between 10 and 11 meters. This does not pose a problem, as the building is initially selected and assigned a value of 10, but when the 11m zone is selected, the building is included in the spatial selection for the 11 meter zone and the 11 meter value is overwritten. Sometimes, buildings are in locations that intersect more than 2 water depth zones. This procedure ensures that the maximum value is always assigned to the building footprint. By calculating the exposure, both necessary components for the inundation ratio analysis, building height and exposure, are ready to be utilized.

3.4 Calculating the inundation ratio

As mentioned in Chapter 2 and the literature review, the inundation ratio stems from tsunami vulnerability assessments and is an important component of many studies (Dall'Osso, et al., 2009b;

Dominey-howes & Dall'Osso, 2009). The inundation ratio is the component of a vulnerability assessment that indicates which percentage of a building is flooded. This attribute shows to what extent a building becomes inaccessible or unusable due to the tsunami flood, thus dealing with the internal part of the building rather than damages to the exterior or the frame of the building.

The inundation ratio is important because it allows spatial investigations that can indicate buildings that are partially flooded and can thus be used as vertical evacuation sites within the flood zone. The criteria of which inundation ratios are acceptable and which are not can vary based on the tsunami scenario, the population or any other parameter set by disaster and evacuation planners. Other than the relative ''safety'' of a building the inundation ratio also indicates how much space within a building is lost due to the tsunami, and how much remains available for evacuations. This way, it is possible to estimate how many people can be accepted into a partially flooded building, in order to save their lives from the tsunami.

The calculation of the inundation ratio requires two values. The first is the building height and the other is the exposure, or the water depth, where the building is located. Thus, the inundation ratio is calculated based on equation 2-2:

Inundation Ratio = (Exposure / Building Height) x100 (2-2)

Multiplying the product of equation 2-2 by 100 gives the result as a percentage which makes it easier to understand and also usable in further calculations as will be shown later.

In this study, there is a total of 4 tsunami scenarios considered. In Chapter 3.2 it was described how the exposure of each building was calculated using spatial selection. This was conducted for all four scenarios, resulting in each building footprint to have four exposure values, one for each scenario. As a result, there is a total of four inundation ratios to be calculated for every footprint, again, one for each scenario. The calculation itself is done within the database, or attribute table, of the building footprint shapefile. Each time, the exposure of a given scenario field is divided by the

building height and multiplied by 100. This results in the final product, which is four inundation ratio fields within the attribute table of the building footprint.

The results of the inundation ratio calculation can be seen in Figures 3-2,3-3, 3-4 and 3-5. The inundation ratio of each building is visualized in classes and it is overlaid on top of its respective tsunami scenario. The produced maps indicate how the buildings with different inundation ratios are distributed spatially. Figure 3-2 shows the case of the 34m run-up scenario. In this case the tsunami waters cover the most part of the city, and as expected many of the buildings are flooded to great extents, or even completely. Moreover, there are many cases where the buildings are flooded completely and there is still a lot of water on top of them. In such a severe scenario, the location where the most buildings with low inundation are found is the CBD of Shizuoka, which is where the tallest buildings are also situated. In the other wards of Shimizu and Suruga, while there are individual buildings with low inundation ratios, they are very scarce, showing that such a scenario can prove to be very difficult to evacuate all residents to safety. The situation is similar but less severe for the 20m run-up scenario as shown in Figure 3-3. Again, the CBD of the city has the most buildings with low inundation ratios, but this time they are even lower, and there are more buildings all over the city that are not completely flooded. There are a few small clusters in Suruga and Shimizu, with buildings that have inundation ratios of 50% or lower. The 10m run-up scenario presents a far less destructive situation, with many buildings within the flood zone having ratios of 50% or less, especially in areas with more shallow waters. Figure 3-4 shows the 10m scenario and the inundation ratios of buildings in Shimizu, as the tsunami goes uphill following the river. In many cases, even very close to the coastline, there are buildings that have low inundation ratios and can be utilized for evacuation. Finally, in Figure 3-5, the 5m run-up scenario shows the same area in Shimizu, where the tsunami flood is far less intrusive and there is a great plethora of buildings that have low or very low inundation ratios that could be potential vertical evacuation sites. The situation is similar in the Suruga Ward and along the coastline of Shizuoka City in its whole. This indicates that the 5m scenario has the most options for vertical evacuation, naturally due to the low severity of the tsunami.

Figure 3-2 Spatial distribution of the inundation ratio of buildings in Shizuoka City, over a 34m run-up.

Figure 3-3 Spatial distribution of the inundation ratio of buildings in Shizuoka City, over a 20m run-up.

Figure 3-4 Spatial distribution of the inundation ratio of buildings in Shizuoka City, over a 10m run-up.

Figure 3-5 Spatial distribution of the inundation ratio of buildings in Shizuoka City, over a 5m run-up.

3.5 Building volume loss and available volume

In the previous sub-chapter it was described how the inundation ratio is the indicator of how much volume of a building is lost after the tsunami flooding happens. This is not entirely accurate as there is need for one more calculation to be conducted in order for the volume loss to be realized and visualized. However, it is important to establish how the volume of a building was calculated for the purposes of this study.

In Chapter 3.1 it was presented that based on the assumption that each floor of a building is 3 meters high, multiplying the number of floors by 3 will result in the building height. Calculating the volume of each building is similar to the above process, but it involves deeper GIS usage. The GIS software is capable of calculating the spatial parameters of shapefiles. This means that for every feature within a shapefile, the software can automatically calculate dimensions such as length or surface. As such, using the Zenrin Zmap Town II 2008/2009 dataset that contains building footprints, it is possible to create a field in the attribute table that will contain the value of the surface of each feature in the dataset. In this case the features are building footprints, which means that the surface of each footprint is essentially the surface of a floor. By performing the above calculation, it is possible to combine its results with the building height in order to introduce the volume of each building. As such, multiplying the surface of each footprint with its height, the volume of each building is assigned as a value to each building.

The calculated volume is the total volume of its building. In order to see how much volume is lost, and consequently how much volume is left after a tsunami happens, all that remains to be done is utilize the inundation ratio as an indicator of volume loss. In other words, the inundation ratio shows the percentage of the volume of a building that is lost due to the tsunami. By subtracting the inundation ratio from the building volume, the remaining building volume is obtained as a result. Equation 2-3 describes the process of subtracting the inundation ratio from the volume of the building:

$$V_A = V_B - [V_B * (Ex / H)] \quad (2\text{-}3)$$

Where V_A is the available volume after the tsunami, V_B is the volume of the building, Ex is the exposure, or water depth at the location of the building, and H is the building height.

This process was done for all four tsunami scenarios and was then visualized into maps. Figures 3-6, 3-7, 3-8, and 3-9, show the results of the volume loss calculation.

The patterns of the volume loss naturally follow the same distribution as the inundation ratio. The advantage of the volume loss, when compared to the inundation ratio, is that it allows for better understanding of how buildings get flooded, in measurable volume units. Moreover, as volume loss is less abstract than the inundation ratio, it is much easier understood when visualized on a map that shows building footprints. Figure 3-6 shows the volume loss that could occur from a 34m run-up tsunami. What can be seen, is that the majority of the city's buildings experience total volume loss due to the extent of the tsunami. Only the CBD of the city which has very tall and large buildings is able of retaining volume within the flood zone available for vertical evacuation. Similarly, Figure 3-7 shows the situation of the 20m run-up scenario. Similarly, the area around the CBD experiences the least volume loss, with scare buildings around the city not experiencing total volume loss. When it comes to the 10m run-up scenario (Figure 3-8), the situation improves greatly, especially in locations with shallow waters where volume loss is minimal. The Shimizu and Suruga Wards show buildings even in deeper waters that do not experience severe volume loss and therefore could be used as potential vertical evacuation sites. The 5m run-up scenario has the least volume loss out of the four scenarios with buildings all over the extent of its flood zone in the Suruga and Shimizu Wards, having enough volume left so that people can evacuate to safety if they reach their higher floors (Figure 3-9).

Figure 3-6 Building volume loss due to a 34m run-up tsunami.

Figure 3-7 Building volume loss due to a 20m run-up tsunami.

Figure 3-8 Building volume loss due to a 10m run-up tsunami.

Figure 3-9 Building volume loss due to a 5m run-up tsunami.

3.6 Ground truthing the endurance of low inundation ratio buildings

The inundation ratio and volume loss are indicators of how a building becomes flooded and to what extent it can be utilized or not as a vertical evacuation site. However, there are other factors that deal with the endurance of a building to a tsunami flood and need to be considered when selecting buildings as vertical evacuation sites. While the purpose of this study is to identify potential vertical evacuation sites within the urban structure, the actual evacuation plan and emergency planning is a procedure that is beyond the time frame and resources of this research. However, it was deemed necessary to conduct a sample field survey in order to catalogue the attributes relevant to the durability of buildings to tsunamis. The underlying idea is that while a building can have a low inundation ratio, factors such as the construction material, or the condition of the building might constitute it unsuitable for use as a vertical evacuation site.

For this purpose, a field survey of 749 buildings was conducted in July 2015, and in two areas of Shizuoka City. The buildings that were selected had an inundation ratio of 50% or less in all four scenarios, and the surveyed areas were along two 500m census tracts in the CBD or center of Shizuoka City in the Aoi Ward, and five 500m census tracts in the center of Shimizu, in the Shimizu ward. The attributes that were catalogued as well as the possible values of those attributes are described in Table 3-2. The purpose of cataloguing the construction material is due to the fact that concrete structures are more durable to tsunamis than wooden ones, for example. A partially inundated concrete building is a safer option than a wooden one which might suffer severe damaging due to the tsunami. Similarly, the condition of a building plays an important role, as abandoned buildings that have been slowly withering can be more susceptible to tsunami destruction. Finally, the building use is for cataloguing purposes only and to get a more detailed overview of the area. As will be explained in Chapter 4, there are datasets that include the building use for the buildings in Shizuoka city.

Table 3-2 Building attributes and attribute values that were catalogued during the field survey of July 2015

Building Construction Material							
Concrete[1]	Steel[2]	Wood[3]	Concrete, Glass Heavy[4]				
Building Condition							
Good[5]	Average[6]	Bad[7]					
Building Use							
Residence[8]	Residential Mixed[9]	Commercial[10]	Commercial Mixed[11]	Office[12]	Parking	School	Hotel

[1]Buildings that are made out of concrete.

[2]Buildings that their frame and walls are made out of steels.

[3]Buildings that their frame is made out of wood.

[4]Buildings that have a concrete frame, but their walls are big glass windows.

[5]Buildings that show little aging and no external signs of damage.

[6]Buildings that show slight sings of aging or slight signs of external wear and damaged.

[7]Buildings that show severe aging and wear or heavy external damage.

[8]Buildings that are of only residential use.

[9]Buildings that are residential but their first floor is used by shops or offices.

[10]Buildings that are of only commercial use.

[11]Buildings that are used for both offices and commerce.

[12]Buildings that are only used as offices.

Starting with the construction material, out of the 357 buildings surveyed around the central Shimizu area, 188 or 53% were made out of concrete, 145 or 41% were made out of wood, and 22 or 6% were made out of steel. This is a mixed situation that shows that concrete buildings and wood buildings are divided in the area of Shimizu. In this case, the concrete buildings are considered to be more resistant to tsunamis, as concrete is a stronger material when compared to wood. As such, wooden buildings should be carefully inspected before being considered for use as vertical evacuation. For example, smaller wooden houses of two floors, might not be suitable for vertical evacuation if they become 50% flooded, as they might be destroyed or moved away from the position. However, larger multi apartment buildings, even though they are made out of wood are stronger and can be durable to tsunamis based on their construction. These are parameters that exceed the scope of this study, however, they need to be pointed out and considered by evacuation experts when a full evacuation plan is established.

Concerning the preservation conditions, 323 buildings, or 91% of the surveyed buildings in Shimizu were of good condition, which means they showed no indication of wear or old age. Another 22 buildings or 6% showed average preservation conditions, which means that they were partially worn or their external features showed their age or were damaged. This means that these buildings regardless of construction material should be carefully considered by engineers as to their ability to provide shelter to tsunami evacuees. Finally, only 10 buildings, or 3%, were found to be in bad condition. In most cases such buildings are uninhabited and are abandoned, having been left to wither away without any care. These buildings should be avoided and not be used for vertical evacuation to tsunamis, as even if their frame is undamaged, the condition of their inside is unknown and might be dangerous to people seeking refuge.

Finally, concerning the use of the buildings that were surveyed in Shimizu, 220 buildings or 62%, were residences, followed by 48 buildings or 14% that had a mixed residential use. These kind of buildings in Shimizu are usually family owned buildings with 2 or 3 floors and the first floor is a family business such as stores or small restaurants. There are, however, larger residential buildings

with many apartments that their first floor consists or more than one businesses, stores or offices. There were few office buildings, with 47 or 13%, of them observed, mostly in close proximity to the Shimizu Station. Similarly, 23 buildings or 7% were of purely commercial use, while parking buildings, hotels and schools, are naturally scarce, accounting only for 4% of the surveyed buildings. The area around the center of Shimizu shows a generally diverse building use, but as will be shown later, it is much more residential than the center of Shizuoka City. Large residential buildings could prove to be crucial as vertical evacuation sites, while office buildings that are of many floors should also be of serious consideration. While there are many smaller mixed use buildings with 2 to 4 or 5 floors, inspection by engineers as to their durability should be conducted before they can be considered as vertical evacuation sites.

Figures 3-10, and 3-11 display maps of sample areas in Shimizu, showing the spatial distribution of the attributes of surveyed buildings.

Figure 3-10 Map of sample area in Shimizu showing the distribution of field surveyed buildings as per their construction material.

Figure 3-11 Map of sample area in Shimizu showing the distribution of field surveyed buildings as per their preservation conditions.

In the center of Shizuoka City, or the CBD, 391 buildings were surveyed. The situation is a lot different when compared to Shimizu, in all three catalogued attributes. First, the construction material is dominated by concrete. As such, 379 or 97% of the buildings were made out of concrete, with only 9 buildings, or 2%, made out of concrete frames but with glass walls and windows. While concrete buildings are considered to be durable to tsunamis, glass heavy structures should be considered with caution, due to the fact that even though a concrete frame is strong, glass is a material that can easily fail to water pressure. Only 3 buildings, or 1% were made out of steel. Other than the glass heavy buildings, concrete buildings can be considered safe enough for vertical evacuation so long as they do not have very high inundation ratios. In the CBD of Shizuoka City, there is an abundance of tall concrete, and therefore durable buildings that can be utilized for vertical evacuation, showing a more uniform condition to the mixed one that is present in Shimizu.

When it comes to preservation conditions, 387 or 99% of the surveyed buildings were of good condition, showing little signs of wear or old age. Only 4 buildings, or 1% seemed to be abandoned and showed severe signs of age and could be potentially dangerous. Generally, the CBD of Shizuoka City is dominated by well preserved structures that as will be shown later are of commercial or office use, and are therefore looked after prudently. As such, most buildings, new or old, are in top condition, posing no danger if used as vertical evacuation sites. Very few buildings are unsuitable which is similar to Shimizu. This indicates that Shizuoka City is a city that is well taken care of by both its residents, as well as its businesses, and only a few minority of buildings can be found in a bad state.

When surveying the building use in the CBD area, it was found that 155 buildings or 40% were of mixed commercial use . These buildings usually have stores in their first floor and offices in the rest of their floors. Sometimes the commercial floors extend to more than the first, but buildings of commercial mixed use are always used for commerce and offices. Following are 150 buildings, or 38%, with pure commercial use. These buildings are often shopping malls or multi floor buildings with only stores or restaurants within them. The next building use is offices, with 42 or 11% of surveyed buildings. These buildings are purely for office use, usually by companies. There is a small

amount of residential buildings in the CBD with 18, or 5% buildings belonging in this category. These are usually tall multi apartment buildings of several floors. The residential mixed use is not as present in the CBD as it is in Shimizu, with only 14 or 4% of buildings being in this category. There are some unusual structures of big shopping malls with multi storied residences on top of them, but they are scarce. In every city center there are hotels, and in the CBD of Shizuoka city 6 of them or 1% were catalogued. The final category was parking buildings with 4, or 1% of them being catalogued in this area.

The CBD of Shizuoka city shows a much different situation than Shimizu when it comes to construction materials and building use. The majority of building in the center are made out of concrete so their utilization as potential evacuation sites does not require extensive engineering surveys. The fact that commerce, office and their mix are the most common building use means that these buildings are usually empty in late evening and night hours, which would make them appealing vertical evacuation sites by residents of areas surrounding the CBD. As will be shown in Chapter 4, the CBD has little population in the evening and night time, and is more populated in the daytime.

Figures 3-12, 3-13 and 3-14 display the spatial distribution of the above attributes, in a selected area of the CBD of Shizuoka City.

Figure 3-12 Spatial distribution of field surveyed buildings in the CBD of Shizuoka City as per their construction material.

Figure 3-13 Spatial distribution of field surveyed buildings in the CBD of Shizuoka City as per their preservation conditions.

Figure 3-14 Spatial distribution of field surveyed buildings in the CBD of Shizuoka City as per their use.

Chapter 4 Building population estimation over 24 hours of a day

4.1 Introduction

Localized population estimation has always been a major geographical subject, with published studies such as Schmitt (1956), attempting to estimate what has come to known as daytime population. The difference between daytime and nighttime population is an important aspect, especially when it comes to natural disasters. As the population within an urban area moves over the course of 24 hours of a day, depending on the time that a disaster occurs, it can have different effects. For vertical evacuation to tsunamis, population movement, but more importantly the population of each individual building is of paramount importance, as a building that might otherwise be safe, can be heavily populated and unable to accept sufficient numbers of evacuees. The importance of a building's population becomes even more apparent when considering the changes in population movement over different periods of the day.

Today, there are various datasets and studies that attempt to capture such shifts in population. Martin et al. (2009) introduce an approach of grid based population models without including the temporal dimension. Badhouri et al. (2007) introduce the LandScan dataset, which has a grid resolution of 90x90 meters, showing population in the day and in the night. However, this resolution is not helpful when the scale unit is a single building. When it comes to microscale analysis, Lwin and Murayama (2009), introduce a model that utilizes larger scale population census data, census tracts of buildings in order to estimate the population of buildings within each population unit by distributing the population based on the volume of each building. However, their approach still lacked the temporal dimension. Using Lwin and Murayama's model as a basis, Greger (2015) introduced a dataset of population movement, in order to estimate the building population over the course of 24 hours of the day in central Tokyo, Japan.

This study uses a similar approach as Greger, as almost all the datasets they used for Tokyo are also available for Shizuoka. However, a dataset of workers census per profession was not available

and the method had to be adjusted to the available datasets, still providing as a result the 24 hour population estimation of buildings in Shizuoka City.

4.2 Estimating building population using census data

The main reason for using building population estimation methods and approaches is the respect of the privacy of people. The majority of statistics agencies around the world do not disclose such information to the public, but rather, they aggregate the data to a certain scale to avoid the invasion of people's privacy. Unfortunately, the population of a building is crucial information for disaster planning, and in this study, knowledge of a building's population allows for better understanding the potential capacity to accept evacuees in case of a tsunami.

Liu et al. (2008) suggest a method of estimating the population of land uses based on satellite imagery and census data (Equation 4-1):

$$P_i = \sum_j d_j A_{ij} \tag{4-1}$$

Where P_i is the population of census unit i, d_j is the population density of land-use type j, and A_{ij} is the area of land-use type j in census unit i (Liu et al., 2008). This approach is the reverse of the one needed, creating census meshes per land use, based on population densities that are either available or collected via field surveys. However, it indicates that utilization of various census data is needed if a microscale population estimation is to be achieved.

Lwin and Murayama(2009), introduce a method of estimating a building's population based on census meshes (or census tracts) and building footprints. This method suggests the reverse of the approach of Liu et al. (2008), utilizing Equation 4-2:

$$BP_i = \left(\frac{CP}{\sum_{k=1}^{n} BA_k \cdot BF_k} \right) BA_i \cdot BF_i \tag{4-2}$$

In this case, BP_i = the population of building i, CP = the census tract population, BA_i = the footprint area of building i, BF_i = the number of floors of building i, i, k = summation indices, and n = the number of buildings that meet user-defined criteria and fall inside the CP polygon (Lwin and Murayama, 2009)(Figure 4-1). This approach can produce results of great relevance to this study, as based on the population census the population of each building can be estimated.

The data requirements for this method are already met. In Chapter 2.2 it was described that building footprints with floor number information are available via the Zenrin Zmap Town II 2008/2009 dataset. Moreover, Chapter 2.7 described the two census mesh datasets of 500m for the residents, or nighttime population, and the workforce or daytime population. In order to use the above approach, it is necessary to distinguish buildings per category. For example, residences can be input in Lwin and Murayama's model, alongside the nighttime census mesh in order to estimate the nighttime building population. As such a distinction between building use was necessary in order to separate the buildings in to two categories, residences and workplaces.

This was achieved by introducing the Telepoint pack of February 2014. The Telepoint pack is a dataset of points, that contain phonebook information. Each point has an address, telephone number and the type of use this number has, for example, residence, restaurant, shop, etc. While it is possible to separate further than residences and workplaces, such an approach was not adopted for two reasons. The Telepoint pack by default separates between two point categories, residences, and all others. It would be possible to group the points as per the use of each telephone number, however the points exceed one million and such an undertaking will be time consuming beyond the capacity of this research. Moreover, there was no census tract data availability for the study area beyond

residences and workplaces, and therefore, separating the buildings in categories beyond those two would be interesting to visualize but redundant to the population estimation method utilized. Figure 4-2 displays the Telepoint data in the CBD area of Shizuoka City.

In order to switch from points to buildings, GIS functions were implemented in order for the Zenrin Zmap Town II footprints to acquire the property of either workplace or residence. This was achieved by selecting all telepoints that were residences, and then applying a spatial selection of all Zenrin footprints that intersect with residence telepoints. The selection result was exported as a new shapefile which contained only residences. Although it was not necessary to separate the footprints into two different shapefiles, such approach proved to be faster when utilizing the method of Lwin and Murayama. The same process was then applied with the workplace telepoints, and the workplace building footprints were extracted into a separate shapefile. Some buildings were found to have multiple telepoints. In the case of the same kind of telepoint this did not make any difference, as a residence with multiple residence telepoints, for example, is still a residence. In the cases where there were workplace and residence telepoints in the same building, the building footprint was included in both the residence and workplace buildings. As will be shown later this results in cases of slight overestimation of building population, however, since the approach of this study is of a worst case scenario nature, overestimations are not considered to be harmful, it would in fact be the opposite, having underestimations that could affect the application of the method's results.

Having two census tracts layers, one for residents and one for workers, and two building footprints layers in corresponding categories, the model of Lwin and Murayama (2009) was applied. What the model does is distribute the population of a census tract in buildings based on their volume, as it is expressed by the surface of its footprint and its number of floors. Buildings with larger volume are assigned larger populations. This is of course not done at random, but based on the formula provided above. What the formula essentially expresses, is that if the volume of a building corresponds to 1% of the total building volume within a census tract, then it will be assigned 1% of the population of the census tract. Running the model for residences and workplaces resulted in two

footprint layers with residents and workers population values per building. The results of running the model and its estimation can be seen in Figure 4-3. This is an area to the north of the CBD of the city, where the orange color indicates residences, and the purple workplaces. Moreover, the number value on top of each building indicates its estimated by the model population.

Lwin and Murayama (2009) recommend that their model could be of use to disaster preparedness and its applications. This study is one of the cases that the model is of great relevance to. The results of the model can be utilized with various GIS approaches. Fore example, Table 4-1 shows the number of buildings, and the estimated daytime and nighttime population within the flood zone of each of the four tsunami scenarios. At this point the model had already been used beyond its initial capacity, by introducing the workforce census tracts and the workplaces footprints. The main shortcoming of the model by Lwin and Murayama (2009) is that it captures a single point in time. In most of the cases the data availability is limited to a resident census but this study made use of the workers census introducing two time zones, daytime and nighttime. However, the population dynamics are much more complex in reality. First off, the change from daytime to nighttime and vice versa is not instant, but is done gradually over certain time periods. Moreover, both populations increase and decrease during the day due to different reasons, and at multiple times per day. As such, if we consider the occurrence of a tsunami, depending on the time it happens, the populations of buildings in the study area should be expected to be different at different times. This indicates the need for a more detailed approach to building population estimation, the kind that encompasses discreet time zones of the day, such as per hour. The following sub-chapters will describe the process followed in this study to accomplish such a population estimation.

Figure 4-1 Graphical representation of the building population estimation model. This study used the volumetric approach, with the number of floors information.

Source: Lwin and Murayama, 2009

Figure 4-2 Sample of the Telepoint Pack of February 2014, in the CBD of Shizuoka City.

Source: Zenrin, 2014 (CSIS).

Figure 4-3 Results of the building population estimation model by Lwin and Murayama (2009), for workers and residents populations.

Table 4-1 Distribution of buildings, and estimated daytime and nighttime populations, per scenario flood zone. The total number of buildings refers is the number of buildings with floor number information that was included in the calculation.

Scenario	Buildings	Workers Population	Residents Population
34m Run up	97,303	326,554	599,367
20m Run up	73,511	277,369	511,458
10m Run up	40,735	142,391	273,497
5m Run up	12,628	54,264	78,503
Total	99,140	344,647	682,130

4.3 The temporal dimension of building population estimation

4.3.1 Introduction

In order to introduce the temporal dimension to building population estimation, Greger (2015) utilized the method of Lwin and Murayama (2009) and incorporated a people flow dataset (Horanont, 2012; Usui et al., 2009; Sekimoto et al., 2011) in order to achieve a building population estimation over 24 hours of a day, at hourly intervals. Greger proposed the following modified formula modified after Lwin and Murayama's volumetric approach (Equation 4-3):

$$BP_{i,c,t} = \left(\frac{AP_{A_{i,c,t}}}{\sum_{k \in A_{i,c}} BA_k \cdot BF_k} \right) \cdot BA_{i,c} \cdot BF_i \qquad (4\text{-}3)$$

Where BPi,c,t is the building population of building i in category c at time t, APAi,c,t is the total population of category c at time t of the census tract that contains building i, A is the set of all census tracts, BAi is the footprint area of building i, BAi,c is the footprint area of building i in category c, and BFi is the number of floors of building i.

The approach uses the people flow data, also known as person trip data, in order to identify people movement in and out of a census tract and adjust its population accordingly in 24 hour intervals, essentially producing 24 sets of census tracts and running the initial model of Lwin and Murayama for each of the 24 census tracts. On top of that, there is a census tract for 6 population categories: home, business and office, education, retail and service, leisure and hotel, and public institution. By adjusting the census tracts of all six population meshes by use of the corresponding categories in the people flow data, Greger was able to achieve a 24h building population estimation.

In this study the approach to the 24h building population estimation is essentially similar to Greger's, however, due to data limitations the categories of census tracts used will be 2 instead of six. As explained earlier, detailed census tracts for different economic activities such as the ones used by

Greger are unavailable for Shizuoka and as will be shown later the people flow data for Shizuoka were grouped into the two categories of Work and Home, in order to match the two available census tract datasets. The details of the building population estimation will be described in detail in the following sub-chapters.

4.3.2 The 2001 people flow data for Shizuoka City

The people flow dataset for the city of Shizuoka is provided by CSIS and it represents the year 2001. The way the dataset was produced from the people of CSIS was by conducting an investigative questionnaire of approximately 71000 people in the central Shizuoka area. The questionnaire involved demographics, such as age, gender and occupation, but more importantly, it asked the participants to describe the way the moved on Monday, October 1st, 2001. That day was a week day, and as such the aim of building such a dataset was to capture how people move over the course of a day.

The respondents of the questionnaire described their daily movement in trips which are segmented in different sub-trips, according to which transportation method they used. For example, home to work is a single trip, but home to station then station to work is two different sub trips of a person going to work. For each trip and sub trip the relevant information were provided by the respondents. This information includes starting and finishing times, as well as the means of transportation of each sub trip. By these, the CSIS were able to incorporate spatial algorithms in order to provide points for the location of each person in one minute intervals. The spatial location of each person was derived by a shortest route algorithm, each time based on the means of transportation the sub trip has. Table 4-2 summarizes the attributes of each point that represents a single person at a given time.

One of the reason that building estimation approaches are utilized are privacy concerns over people's residences, workplaces etc. For the same reasons the CSIS conducted generalizations at the starting points and ending points of each respondent's trips, so that any privacy concerns could be

minimized. This way, if a respondent starts a trip by leaving his home for example, the starting point is represented the block where their home is rather than the actual home itself. This poses no issues to the estimation method used in this study, as the main focus is the census tracts, which then lead to the building population estimation, so the generalized starting and ending points do not affect the scale that the census tracts are available.

Concerning the year that the data was obtained, 2001 was 14 years ago which would normally mean that there should be inconsistencies with the population movement back then and today. Looking at the population of Shizuoka City from the year 2003 to today, while there has been an increase in population of about 20.000 residents, this increase is but a small fraction of the total population of the city. Moreover, the sample of the person trip data itself is larger than the population increase. As such, the 14-year-old people flow data should still be representative of people's movement today.

When considering the movements of people in Shizuoka in a single day it is possible to summarize the majority of activities in a single graph and for the whole sample, over the course of 24 hours of a day. Figure 4-4 summarizes the movements of Shizuoka City's residents by trip purpose as described above. What this figure indicates is that the majority of residents in the city of Shizuoka start their day at home but from around 6 am they start going to work and school. The amount of people on their way to work or school peaks at 8 am and then gradually decreases at 10am. There are other work categories that are not included in the ''to work'' category in the data, and they follow the same trend. Other activities such as shopping or recreation peak later at 10am and continue almost stable during the course of the day, stopping only after 20pm. The work and school trips fluctuate on low levels during the day. This could be due to the fact that there are jobs and schools that do not follow a strict 9am-17pm schedule as most businesses and schools do. However, on closer examination of the trips to work and school there is a small peak at around 13pm. This can probably be explained by the fact that many people return to school or work after their lunch break.

The lunch break is also visible in the trips towards home. Generally speaking, the trip of returning home start at 15pm but they are low, but they steadily increase to their peak at 17 and 18pm. After that the home trips decrease steadily and the majority of the population seems to be home by 21 or 22pm. After that any returns home are probably late workers or people returning after recreation. There is a small peak of trips to home, starting from 11 am and peaking at 12pm. This is probably the same thing that was discussed above, indicating that people do not just go for lunch outside or at their workplace, but they have the ability to return at home for lunch.

These variations in the population movement are important for vertically evacuating to buildings showing that different buildings are expected to have different populations throughout the day. Spatially, the amount of people entering and exiting a census tract, is an important indicator of how population increases locally throughout the day and per building use. The following sub-chapter will describe how the person trip data was used in order to adjust the residents and workers' census tracts expanding them to 24 per category, one for each hour of the day.

Table 4-2 Attributes and values of the points in the 2001 person trip data of Shizuoka. Data source: CSIS

Gender			
Code	Value		
1	Male		
2	Female		
9	Unknown		
Age			
Code	Value	Code	Value
0	0-5	9	45-50
1	5-10	10	50-55
2	10-15	11	55-60
3	15-20	12	60-65
4	20-25	13	65-70
5	25-30	14	70-75
6	30-35	15	75-80
7	35-40	16	80-85
8	40-45	17	85 and up
Occupation			
1	Agricultural/forestry/fishery	9	Professional
2	Mining business	10	Manager
3	Labor/Factory(Blue Collar)	11	Other Workers
4	Sales	12	High School Student
5	Service	13	College Student
6	Transport Service	14	House-Wife
7	Security Service	15	No-Occupation
8	Office Worker	98	Others
		99	Unknown
Purpose			
1	To-from office	11	Delivery of documents
2	To-from school	12	For selling and buying
3	To home	13	For buying in and purchase
4	To return to school/work place	14	To/for work (fixing and repairing)
5	For short recreation	15	For agriculture, forestry and fisheries job
6	For lessons and private school	16	To send/pickup activity
7	For recreation/Shopping	17	For inspection survey and house call
8	To send/pick up activity and social meeting	98	Other business
9	Tourism and recreation	99	Unknown
10	Meeting and conferences		
Transportation mode			
1	Walk	9	Private Bus
2	Bicycle	10	Public Bus
3	Motor-Bicycle	11	Monorail Transit
4	Motor-Bike	12	Train/Subway
5	Taxi	13	Ship
6	Passenger Vehicles	14	Aircraft
7	Mini Car	97	No movement
8	Freight Vehicle	98	Others
		99	Unknown

Figure 4-4 Person trip movements per trip purpose over the course of 24 hours of a day for the Shizuoka Metropolitan Area.

Data source: CSIS, 2001

4.3.3 Adjusting population census tracts to 24 hourly intervals

As described in sub chapter 4.3.1 in order to estimate the building population over 24 hours of the day sing the method of Greger (2015), the population census tracts need to be expanded from a single moment in time, in this case daytime and nighttime, into 24 time intervals, each representing a single hour of the day.

For this purpose, it was necessary to use the person trip data for Shizuoka City in order to filter the people that were stationary at 24 hour intervals. The points that are stationary people do not have a purpose trip and in this case, the purpose of their trip was deduced by examining the purpose of their trip immediately their becoming stationary. However, given the fact that there are two census tract types, workers and residences, the person trips that were described in the previous sub-chapter had to be grouped together to form three categories: Work, Home and Leisure (Figure 4-5). The leisure category was not included in the census tract adjustment process as it is completely random in relevance with the others. While it is discreet during time it can be expressed spatially at many different locations that oftentimes are not even buildings such as parks or other open locations.

The person trips for work and home were then subsequently aggregated in 24 time slots, which, simply put, is an index of how many people enter a census tract, and how many people exit it. The maximum value of population was defined as the 100% index and therefore the fluctuations of the person trip populations were extrapolated and applied to the workers and residents mesh adjusting the census tracts' population value and producing 24 census meshes for the residents and 24 census meshes for the workers.

Having the new census tract dataset, it was only a matter of running the original model by Lwin and Murayama, 48 times, 24 for the residence footprints and 24 for the workplace footprints. This resulted in each footprint acquiring 24 population attributes one for each time of the day. Both Lwin and Murayama's approach as well as Greger's are applied based on the assumption that the fluctuations of population within each census tract are also happening to all buildings within the census tract. For example, if at 5am the residents' population of a census tract is at 100% and the

population at 11am is at 20%, then all the buildings will be at 20% of their population. Figure 4-6 presents the flowchart of this 24h population estimation process, via the utilization of the person trip data, the census tract adjustment and reaching the final result. Figures 4-7 and 4-8 show two different times of the day and their respective building population estimation. The first figure shows the population at 11am, in the CBD of Shizuoka City. During that time, the buildings which are heavily populated are workplaces, while the residences are still partially populated but with low populations. In contrast, the second figure at 17pm shows greatly reduced populations in the buildings that are workplaces and increased populations in the residences, as by this time many people have already returned home.

Figure 4-5 Grouped person trips for work, home and recreation over 24 hours in the city of Shizuoka.

Figure 4-6 Flowchart of 24h building population estimation through census tract extrapolation.

Figure 4-7 Building population estimation in the south of the CBD area of Shizuoka city at 6am.

Figure 4-8 Building population estimation in the south of the CBD area of Shizuoka city at 12pm.

4.3.4 Validation

The estimation of the 24h building population estimation provided results for all footprints with floor number information in the city of Shizuoka. The adaptation of Greger's (2015) approach with only 2 building use categories had to be tested with actual real life data. In the case of Lwin and Murayama (2009) the researchers had actual building population data for the area that they applied their estimation method. By having such data, they were able to compare the estimated values with real values, proving a very solid correlation between the two. In the case of Greger (2015), the estimated values had to be tested by monitoring buildings as per how many people enter and exit and thus calculating the population per hour in the time frame between 7am and 2pm of a single day. The field observations showed that the model overestimated population values in the early hours of the morning but in the rest of the hours the day, the model estimations were very close to the observed values in the field.

For this research a similar approach was implemented. In this case two buildings were selected, one in the CBD of Shizuoka City and one in the center of the Shimizu Ward. For privacy reasons, the exact location and images of these buildings will not be revealed, but their qualitative characteristics will be described with discretion. Also for privacy reasons, the buildings that were selected were workplaces, namely office buildings, as the privacy of people in residential buildings is of utmost importance.

As such the two office buildings were monitored from 7am until 22.30pm at night. Building A (Shimizu Center) is an office building with three entrances. The two entrances are regular doors and the third one is via garage, with people entering by car. The building estimation method shows a maximum population of 40 people, which is relatively small for a 5 floor building. However, upon close inspection, the office building had only half of its space occupied by companies, and the rest of the space was up for rent therefore, unoccupied. Figure 4-9 shows the estimated and observed population of the building over the course of a day. What can be seen is that the model overestimates in the early hours the number of people arriving in, expecting double the amount of people than the

ones actually arriving at 8am, while at 9am the observed and estimated values are very close. The estimated values and the observed values show a similar drop during lunch time which shows that this population shift has been estimated justly, but slightly overestimated. Both the observed and estimated values match in decrease until 17pm which is naturally expected in an office building. However, in the case of Building A, the method was unable to predict the fact that one of the offices had a party organized, with guests arriving steadily after 18pm and finally the building emptying between 10pm and 10.30pm. While this underestimation is a fact, it is also a fact that no dataset exists that can provide real time, or modelled or any other way obtained data of such social events in buildings and as such, other than the party, for the majority of time there seems to be a good correlation between the estimated and the observed values.

Proceeding to Building B and the CBD of Shizuoka city, this building was also a 5 floor office building, this time belonging in its whole to a bank. Similar to Building A, the model overestimates the population at 8am compared to the actual population but the population at 9am when the bank opens has similar observed and estimated values. This overestimation in both buildings can be attributed to the nature of the person trip data and the hourly segregation of the day. While there are a lot of people at 8am on the way to work, they might have not yet arrived, and they are captured by the data and the method at 8am, even though they arrive at 9am. At times of the day the observed values exceed the estimated ones. This is due to the fact that the bank building is open to clients, and at while clients come and go generally keeping the population of the building steady, there are hours such as 10am and 11am where there were many clients served and the population had higher values than the estimated one. While the bank closes at 17pm, there were still many workers working overtime even at 20pm, of which the estimated values did not match the reality. Of course, anticipating the overtime pattens of a whole city is not an easy task, and again, cannot be reflected in any dataset currently available for this scale.

Both buildings were selected for their view to all entrances and to the fact that their small population was suspicious compared to their size. Moreover, buildings such as shopping malls or

very big office compounds have too many entrances, sometimes even underground, through parking lots etc, that would make the observation of their actual population impossible. Disproving the initial suspicions, the method approximated the maximum observed values closely, indicating at a phenomenon that was observed during field word empirically. Many commercial buildings in all wards of Shizuoka city, including the CBD, are occupied only to half their extent. There are office buildings and shop buildings half used, or completely empty or used to smaller extents. The residential buildings of the city did not seem to be in the same situation. This phenomenon cannot be explained by simple demographics and its explanation falls beyond the scope of this research. However, it offers an important contribution to vertical evacuation and that is space. Having so many buildings half utilized, means that there is a lot of unused space that can be useful in case of a vertical evacuation. Buildings that are partially occupied could accept large numbers of evacuees potentially saving many more lives in the process. The estimated amounts of people that can be accepted in buildings per hour is the focus of Chapter 5.

Figure 4-9 Estimated and observed values of the population of Building A, in the Center of Shimizu Ward.

Figure 4-10 Estimated and observed values of the population of Building B, in the CBD of Shizuoka City.

Chapter 5 Analyzing the potential for vertical evacuation

5.1 Introduction

Up to this point this study has managed to use GIS approaches and techniques in order to estimate two components that are crucial when evaluating buildings as potential vertical evacuation sites. Though different components can be considered, without those two, any analysis lacks the most important information of whether a selected building is flooded or not, and how many people are expected to be in it. This research has achieved calculating and estimating both, and especially for the latter, it has estimated it over 24 hours of a day.

Up to this point however, there has been little utilization of the two components. Therefore, the final step of this research is to use the components in order to analyze the potential for vertical evacuation. This will be done by introducing criteria for each tsunami scenario and each component, and based on these criteria it will be estimated how many people can fit in the selected vertical evacuation sites during different times of the day. The criteria selection conducted in this study is not based in extensive evacuation plan research. This is due to the fact that the approach of this research is applied for the first time, even though its components have been used in other studies, irrelevant to vertical evacuation. A fully planned and organized evacuation plan is outside the scope of this study, as it requires the collaborations of several specialties and extensive human resources. However, this study can provide the framework and the appropriate tools of quickly finding vertical evacuation sites in an existing urban structure and estimating how many people are expected to be in them during different times of the day, and how many more people can be accepted if there is need for evacuation.

5.2 Criteria and assumptions

Due to the fact that the approach of this research uses estimation tools, it is necessary to make certain assumptions when selecting criteria for vertical evacuations. Starting with the tsunami scenarios, the 34m and 20m run-up ones are considered to be severe scenarios that affect the city in its whole. In Chapter 3, it was discussed how these scenarios flood a great part of the city causing

increased volume loss to the buildings in all extent of their flood zone. In this case, due to the severity of these scenarios, the potential evacuation sites that will be accepted will have an inundation ratio of 75% or less. This makes sure that very tall buildings will still have floors that are not flooded, and that they can be utilized for local residents to protect their lives. This also allows for availability of some evacuation sites closer to the coastline, where the tsunami flood would be expected to be deeper.

For the 10m and 5m run up scenarios, the evacuation criteria will be stricter. This is due to the fact that the flood zones are neither as deep nor as extensive as the 34m and the 20m run up scenarios. Moreover, the inundation ratios of buildings in the flood zones of both scenarios show much less volume loss all across these two scenarios. Therefore, for the 10m and 5m run up scenarios, the considered evacuation sites are the ones that have an inundation ratio of 25% or less. Since the scenarios are smaller with less volume loss, this ensures safer evacuation sites and much more available volume for evacuation within the flood zone.

The building population estimation allows the anticipation of the amount of people in each building. By setting criteria for how much volume is allocated to each person when evacuating it is possible to estimate how many people can fit in the available volume after the tsunami. In this case, variable evacuation criteria can be introduced in order to have multiple results, out of which an acceptable state can be selected. For this reason, this study will consider assigning 3 cubic meters, 6 cubic meters or 9 cubic meters per person. The case of the 3 cubic meters can be considered a worst case scenario where people will have to be extremely congested in order to save themselves, while the 6 cubic meter case is a less congested option, and finally the 9 cubic meter per person case is an option for evacuating people in with increased comfort of space.

5.3 Criteria application and vertical evacuation analysis

5.3.1 Vertical evacuation analysis calculations

As described in the previous sub chapter different acceptable inundation ratios are selected for different scenarios, but for each scenario the number of people that can be accepted will vary depending on the cubic meters allocated per person. Given the fact that the population of each building is not the same at different times of the day, for a given time X the number of people that can be accepted is calculated by Equation 5-1

$$\mathbf{N= [(V_B - IR) - (P_{BX} * V_E)]/V_E} \qquad (5\text{-}1)$$

Where N is the number of people that can be accepted by the building, V_B is the volume of the building, IR is the inundation ratio of the building, P_{BX} is the population of the building at time X, and V_E is the volume allocated per person for evacuation.

The application of the above formula can be done for the whole of Shizuoka City by GIS, and for the buildings that have floor numbers and their 24h population and inundation ratio has been estimated. The above calculation shows the amount of volume of a building that is lost due to the tsunami, and the amount of volume that is required for the people that are already situated within the building. The rest of the available volume can be utilized to accept people that are seeking to evacuate from an incoming tsunami, and can vary based on the time or strictness of the criteria

5.3.2 Results

The results of this analysis are heavily dependent on the criteria set by the evacuation planners. For this research the following criteria were set per scenario:

- 34m run-up scenario: 75% or less inundation ratio, 3, 6 or 9 cubic meters per person
- 20m run-up scenario: 75% or less inundation ratio, 3, 6 or 9 cubic meters per person

- 10m run-up scenario: 25% or less inundation ratio, 3, 6 or 9 cubic meters per person
- 5m run-up scenario: 25% or less inundation ratio, 3, 6 or 9 cubic meters per person

Based on this criteria, the calculation described in sub Chapter 5.3.1 was conducted using GIS. The Zenrin Zmap Town II 2008/2009 footprints for the city of Shizuoka initially contained only floor number information. From the calculations conducted in Chapters 3 and 4, the footprints now contain information for each building that include: 4 inundation ratios, 4 volume losses, and population for 24 hours of the day. By adding the above calculation, each building now has information on how many people can fit on top of the existing people based for 3 different criteria.

While these results are available for single buildings, presenting such results is impossible without generalizing. For this reason, the total amount of evacuation sites per scenario (Table 5-1), and the total amount of people that can be accepted at every hour of the day were calculated. Tables 5-2, 5-3, 5-4 and 5-5, summarize this information. Moreover, the results of this calculation can be visualized in 24h transition maps. Figure 5-1 shows the potential evacuation sites for the 20m scenario, with inundation ratio of 75% or less, and how the population in them is at 6am. In comparison, Figure 5-2 shows the same potential evacuation sites and how the population has shifted to different buildings at 12pm. For the full transition of building population from 6am till 9pm see Appendix I. While the results of the analysis will be discussed in the following sub chapter, it is worth mentioning that there are 10,426 potential evacuation sites with inundation ratio of 75% or less. These are all evacuation sites within the tsunami flood zone. In comparison, the designated evacuation sites in the flood zone are 200, and these are without including the open areas that are unusable.

Table 5-1 Currently designated evacuation sites by the Japanese Government and potential evacuation sites resulting from the methodology of this study in the flood zone of each tsunami scenario.

Scenario	34m	20m	10m	5m
Current designated sites	258	200	108	27
Potential sites	3,204	10,426	2,046	1,643

Figure 5-1 Evacuation sites with inundation ratio of 75% or less in the 20m tsunami scenario in the CBD of Shizuoka city, and their population at 6am.

Figure 5-2 Evacuation sites with inundation ratio of 75% or less in the 20m tsunami scenario in the CBD of Shizuoka city, and their population at 12pm.

Table 5-2 Total population of people already in potential evacuation sites, and additional population that can be accepted over 24 hours of a day. in the 5m scenario and inundation ratio of 25% or less.

5m Scenario - 1643 potential sites																	
Population already in buildings																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
	28780	28437	26285	21514	19793	11757	11936	19213	11560	18373	19129	21092	23119	25909	27301	28235	28711
Potential for additional population																	
Total																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
$3m^3$ per person	565140	565826	570130	579674	583114	608948	609468	584274	599580	559830	558278	580518	576462	570882	541584	566230	565278
$6m^3$ per person	282570	282913	285065	289837	291557	304474	304734	292137	299790	279915	279139	290259	288231	285441	270792	283115	282639
$9m^3$ per person	188380	188608	190043	193224	194371	202982	203156	194758	199860	186610	186092	193506	192154	190294	180528	188743	188426
Residences - 1233 potential sites																	
$3m^3$ per person	294644	295598	303424	321514	327804	338236	338756	329828	345704	332372	329444	322938	315188	305320	299938	296002	294566
$6m^3$ per person	147322	147799	151712	160757	163902	169118	169378	164914	172852	166186	164722	161469	157594	152660	149969	148001	147283
$9m^3$ per person	98214	98532	101141	107171	109268	112745	112918	109942	115234	110790	109814	107646	105062	101773	99979	98667	98188
Workplaces - 410 potential sites																	
$3m^3$ per person	270496	270228	266706	258160	255310	270712	270712	254446	253876	227458	228834	257580	261274	265562	241646	270228	270712
$6m^3$ per person	135248	135114	133353	129080	127655	135356	135356	127223	126938	113729	114417	128790	130637	132781	120823	135114	135356
$9m^3$ per person	90165	90076	88902	86053	85103	90237	90237	84815	84625	75819	76278	85860	87091	88520	80548	90076	90237

Table 5-3 Total population of people already in potential evacuation sites, and additional population that can be accepted over 24 hours of a day. in the 10m scenario and inundation ratio of 25% or less.

10m Scenario - 2046 potential sites																	
Population already in buildings																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
	53778	53010	47937	36432	32261	16719	16980	30922	16445	29086	30910	35412	40364	46892	50294	52672	53719
Potential for additional population																	
Total																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
$3m^3$ per person	1705663	1706429	1711506	1723006	1727181	1746543	1747074	1728518	1742996	1730357	1728532	1724028	1719077	1712547	1709145	1706767	1705722
$6m^3$ per person	852831	853214	855753	861503	863590	873271	873537	864259	871498	865178	864266	862014	859538	856273	854572	853383	852861
$9m^3$ per person	568554	568809	570502	574335	575727	582181	582358	576172	580998	576785	576177	574676	573025	570849	569715	568922	568574
Residences - 1551 potential sites																	
$3m^3$ per person	1020188	1021151	1028751	1046387	1052619	1060913	1061444	1054562	1069447	1057013	1054177	1047813	1040216	1030600	1025366	1021489	1020092
$6m^3$ per person	510094	510575	514375	523193	526309	530456	530722	527281	534723	528506	527088	523906	520108	515300	512683	510744	510046
$9m^3$ per person	340062	340383	342917	348795	350873	353637	353814	351520	356482	352337	351392	349271	346738	343533	341788	340496	340030
Workplaces - 495 potential sites																	
$3m^3$ per person	685475	685278	682755	676619	674562	685630	685630	673956	673549	673344	674355	676215	678861	681947	683779	685278	685630
$6m^3$ per person	342737	342639	341377	338309	337281	342815	342815	336978	336774	336672	337177	338107	339430	340973	341889	342639	342815
$9m^3$ per person	228491	228426	227585	225539	224854	228543	228543	224652	224516	224448	224785	225405	226287	227315	227926	228426	228543

Table 5-4 Total population of people already in potential evacuation sites, and additional population that can be accepted over 24 hours of a day. in the 20m scenario and inundation ratio of 75% or less.

20m Scenario - 10426 potential sites																	
Population already in buildings																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
	115280	114322	107974	94934	91080	59797	60718	89265	58830	85967	88313	93733	99499	107632	111339	113758	114931
Potential for additional population																	
Total																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
$3m^3$ per person	5587754	5589666	5602380	5628454	5636164	5764030	5765984	5639800	5700666	5646396	5641706	5630852	5619320	5603058	5595638	5590794	5588454
$6m^3$ per person	2793877	2794833	2801190	2814227	2818082	2882015	2882992	2819900	2850333	2823198	2820853	2815426	2809660	2801529	2797819	2795397	2794227
$9m^3$ per person	1862584	1863222	1867460	1876151	1878721	1921343	1921994	1879933	1900222	1882132	1880568	1876950	1873106	1867686	1865212	1863598	1862818
Residences - 7969 potential sites																	
$3m^3$ per person	3240792	3243964	3273092	3339272	3360892	3416078	3418032	3368452	3431862	3378938	3367750	3344222	3315658	3279216	3259582	3245092	3240502
$6m^3$ per person	1620396	1621982	1636546	1669636	1680446	1708039	1709016	1684226	1715931	1689469	1683875	1672111	1657829	1639608	1629791	1622546	1620251
$9m^3$ per person	1080264	1081321	1091030	1113090	1120297	1138692	1139344	1122817	1143954	1126312	1122583	1114740	1105219	1093072	1086527	1081697	1080167
Workplaces - 2455 potential sites																	
$3m^3$ per person	2346962	2345702	2329288	2289182	2275272	2347952	2347952	2271348	2268804	2267458	2273956	2286630	2303662	2323842	2336056	2345702	2347952
$6m^3$ per person	1173481	1172851	1164644	1144591	1137636	1173976	1173976	1135674	1134402	1133729	1136978	1143315	1151831	1161921	1168028	1172851	1173976
$9m^3$ per person	782320	781900	776429	763060	758424	782650	782650	757116	756268	755819	757985	762210	767887	774614	778685	781900	782650

Table 5-5 Total population of people already in potential evacuation sites, and additional population that can be accepted over 24 hours of a day. in the 34m scenario and inundation ratio of 75% or less.

34m Scenario - 3204 potential sites																	
Population already in buildings																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
	43902	43693	42917	42338	42101	31111	31613	41803	30601	41142	41144	42154	42355	43297	43444	43488	43609
Potential for additional population																	
Total																	
Time	5am	6am	7am	8am	9am	10am	11am	12pm	13pm	14pm	15pm	16pm	17pm	18pm	19pm	20pm	21pm
$3m^3$ per person	1831444	1831653	1832429	1833008	1833245	1864952	1865315	1833550	1844750	1834210	1834208	1833198	1832996	1832055	1831907	1831863	1831743
$6m^3$ per person	915722	915826	916214	916504	916622	932476	932657	916775	922375	917105	917104	916599	916498	916027	915953	915931	915871
$9m^3$ per person	610481	610551	610809	611002	611081	621650	621771	611183	614916	611403	611402	611066	610998	610685	610635	610621	610581
Residences - 2481 potential sites																	
$3m^3$ per person	1141508	1142070	1147133	1158321	1162142	1174717	1175080	1163487	1175384	1165197	1163444	1159192	1154442	1148184	1144814	1142276	1141504
$6m^3$ per person	570754	571035	573566	579160	581071	587358	587540	581743	587692	582598	581722	579596	577221	574092	572407	571138	570752
$9m^3$ per person	380502	380690	382377	386107	387380	391572	391693	387829	391794	388399	387814	386397	384814	382728	381604	380758	380501
Workplaces - 723 potential sites																	
$3m^3$ per person	689935	689582	685295	674686	671102	690234	690234	670063	669366	669013	670764	674006	678554	683871	687093	689587	690239
$6m^3$ per person	344967	344791	342647	337343	335551	345117	345117	335031	334683	334506	335382	337003	339277	341935	343546	344793	345119
$9m^3$ per person	229978	229860	228431	224895	223700	230078	230078	223354	223122	223004	223588	224668	226184	227957	229031	229862	230079

5.4 Results discussion

5.4.1 Number of potential sites and available volume

The previous chapter described in detail the results of the potential vertical evacuation analysis. By setting different criteria with variable strictness depending on the severity of the scenario, it was possible to identify potential vertical evacuation sites that were not flooded completely and that they could be used in the event of a tsunami. Table 5-1 summarizes the potential evacuation sites found per scenario flood zone, but also the current designated evacuation sites within each scenario flood zone. The results show that while there are 258 designated evacuation sites, there are 3,204 potential vertical evacuation sites with inundation ratio of 75% or less. This is 12 times the number of the currently designated sites. The results continue in similar fashion with the rest of the scenarios. In the case of the 20m scenario, there are 200 designated and 10,426 potential evacuation sites in the flood zone. For the 10m scenario there are 108 designated sites and 2,046 potential sites. Finally, in the case of the 5m scenario, there are 27 designated and 1,643 potential evacuation sites.

In many cases the designated evacuation sites have inundation ratios of 100% which means that they would be useless in some scenarios. On the other hand, all potential evacuation sites are ensured to be not completely flooded based on the inundation ratio calculation method, the selection criteria and the tsunami scenarios. What was also found was that some of the currently designated evacuation sites were included in the results, but such cases were few. As far as the number of the potential evacuation sites the approach used in this research has managed to find far more potential evacuation sites than the ones that are currently designated. This does not necessarily mean that all of the found building should be adopted for use immediately as there are other factors that should be considered. However, considering all buildings on the urban structure of the city of Shizuoka for this analysis shows that there is the potential for many more options.

Concerning the amounts of people that can be accepted in the potential evacuation sites, the stricter the space assigned to each person the more people can fit in the available building volumes. The 3 cubic meter per person criteria results to more people being able to be accepted in all four

scenarios, than the 6 cubic meter or the 9 cubic meter per person cases. Perhaps 3 cubic meters per person describes a situation of extreme congestion of people, but in this case, the 5m scenario potential evacuation sites could accept a maximum of 608,948 people at 10am in the morning and a minimum of 541,574 people at 19pm in the evening. This is a staggering amount of people – approximately 84% of the population of Shizuoka City for 10am and 75% for 19pm. By assigning 6 cubic meters per person, 304,474 people or 42% of the population of Shizuoka City can be accepted at 11am and 272,792 or 385 of the population of the city can be accepted at 19pm. For the case of 9 cubic meters per person, 202982 or 27% of the city's population can be accepted at 10am and 180528 or 24% of the city can be accepted in the volume available. These numbers are for the scenario with the least extensive flood zone, and as such would require the least number of evacuation sites. Even at the case of 9 cubic meters per person, which is essentially a whole house room per evacuee, at 19pm that has the least volume available, the amount of people that can be accepted in the smallest scenario is almost double the one of the currently designated sites. In the case of the 10m scenario the numbers when assigning 3 cubic meters per person reach a staggering 1,746,543 people that can be accepted at 10am in the morning, meaning that the population of about 2,4 Shizuoka Cities could be accepted. In contrast, 569,715 people could be accepted in the potential vertical evacuation sites when assigning 9 cubic meters per person and at 21pm this time, meaning that 79% of the city's population could fit in the volume of those potential vertical evacuation sites. In the 20m scenario, the maximum amount of people that can be accepted is 5,764,030, at 10am and at 3 cubic meters per person, allowing for almost 8 times the total population of Shizuoka city to be accepted. At 21pm and at 6 cubic meters per person, 1,862,818 people or 2.5 times the population of Shizuoka City, can be accepted which constitutes the minimum for the 20 m scenario. Finally, in the case of the 34m scenario the maximum amount of people can be accepted for evacuation at 10am and at 3 cubic meters per person, with 1,864,952 people or 2.6 times the population of Shizuoka City, while the minimum is reached at 21pm with 610,581 people or 84% of the population of Shizuoka.

These numbers are very large especially when considering how much larger they are compared to the approximately 112,000 people which is the capacity of the currently designated vertical evacuation sites. There are many reasons behind these numbers, the most obvious of which is that considering all buildings in the urban structure of Shizuoka City allows for far more many options than just schools or government buildings permit. Moreover, the 20m and 34m scenarios benefit from very large amounts of large buildings in the CBD and its surrounding area such as shopping malls etc., which have larger volumes compared to residences. Also, the largest numbers are found when assigning 3 cubic meters per person. This situation cannot be actually realized as it would mean people congesting themselves to great extents, regardless of the scale of the emergency. However, should this distribution be achieved, it could save the most amounts of lives in the most catastrophic scenarios. On the other hand, the case of 9 cubic meters per person, while it still offers more options than the currently designated sites, it is not always enough to cover the population of Shizuoka City in its majority. The case of the 6 cubic meters per person seems to be more fitting in all scenarios, and perhaps assigning a volume around this value could provide the best vertical evacuation results.

5.4.2 Spatial and temporal aspects of vertical evacuation

Concerning the 24 hour population time estimation, in Tables 5-2 to 5-6, the information of how many people are already inside the potential vertical evacuation site buildings can be found. It is obvious that there are fluctuations throughout the day. The morning hours between 9am and 11am are the ones that have the least amount of people inside the vertical evacuation sites. This means that these hours can potentially provide the most space or volume for vertical evacuation. The reasons behind this could possibly be identified in the fact that during those hours there are people out for leisure activities such as shopping etc. Moreover, many of the vertical evacuation sites are residences, which means that as people go to work in other locations, they leave buildings with lesser populations behind. This can be further backed by the fact that the residences in Shizuoka City are greater in numbers than the workplaces, and the empty residences of the morning hours could have more empty

volume that can be used for vertical evacuation. Tables 5-2 to 5-6 show that the potential vertical evacuation sites that are residences are greater in numbers than the ones that are workplaces in every scenario, resulting in the above described situation.

Up to this point, it has been described that there are high values of available volume available for vertical evacuation in each scenario, and that there are discreet fluctuations of the available volume during different times of the day. While these numbers can be considered to be satisfactory based on the scenarios and vertical evacuation criteria, it is of equal importance to examine the spatial distribution of these vertical evacuation sites per scenario. Figure 5-3 summarizes the clusters formed by the potential vertical evacuation sites per tsunami scenario. In this figure, it becomes obvious that different tsunami scenarios have different clusters of vertical evacuation sites. The severe scenarios have a discreet clustering of potential sites that is limited in the area of the CBD for the 34m scenario and the area surrounding the CBD for the 20m scenario. This situation can be attributed to two factors. First, the extent of the tsunami flood zones and the extreme water depths in these scenarios which result in the flooding of the buildings in the majority of the areas found in this tsunami flood. Second, the tallest buildings are found in the CBD of Shizuoka city and its surrounding areas, which results in these areas being the only ones that have available buildings for vertical evacuation in such extreme scenarios.

On the other hand, in the weaker 10m and 5m scenarios, the clustering of the potential vertical evacuation sites is much wider, and in both cases it covers the majority of the extent of the flood zones of these scenarios. This is in contrast with the severe scenarios where only a small part of the tsunami flood zone has available potential sites. This results in a far better situation than the severe scenarios where potential evacuation sites are available almost everywhere within the flood zone, allowing for potential vertical evacuation with minimal required movement. The required movement for vertical evacuation is the exact opposite in the severe scenarios. In these cases, vertical evacuation would require movement towards the CBD area in both the 34m and 20m scenarios, otherwise vertical

evacuation is impossible. This movement, especially from areas closer to the coastline might be very time consuming as the distances between the CBD and the coastline are very large.

There is a complex but apparent relationship between the time that the tsunami happens, its severity, and the available potential sites. This relationship is summarized in Figure 5-4, and it describes the possible vertical evacuation movements during different times of the day. If the tsunami happens during the evening or late at night, many of the residents of Shizuoka City have returned to their homes, and if the tsunami is not severe (5m or 10m run up scenarios), the residents can find an empty workplace close to where they live in order to vertically evacuate. As described earlier, this can be done at the full extent of the non severe tsunami flood zones. In many cases, movement to a different building might not be necessary, as the building that one lives could already have the characteristics of a potential vertical evacuation site. In contrast, the situation of the severe scenarios (34m and 20m run-up) is the exact opposite. Due to the severe flooding of the city, only the CBD area has potential vertical evacuation sites, and people from the full extent of the city have to move toward the CBD to vertically evacuate. This movement can be time consuming based on the distance from the CBD and the nature of the road network of the city. Empty workplaces are recommended for vertical evacuation in this case.

The problem of the need to travel towards the CBD is somewhat limited during the daytime due to the fact that people concentrate in the CBD of the city in order to work. This means that if a severe tsunami happens during the daytime, many people are already in the CBD for work, or recreation and they need to vertically evacuate in a potential vertical evacuation site, if they are not already in one. During the daytime, residences in the CBD surrounding area are emptier and are recommended for vertical evacuation. This better situation during the daytime does not solve the problem completely, as there are many people that do not go to work, or work in close to the coastline in areas such as Shimizu or Suruga. These people will still have to move towards the CBD to vertically evacuate during such severe scenarios. In the case of the weaker scenarios, the situation is similar to the nighttime, but in this case, vertical evacuation is recommended to buildings that are residences as

they are expected to be emptier in the morning and noon hours. In the weaker scenarios, there are potential vertical evacuation sites covering the extent of the flood zones in these cases, and movement towards the CBD is not necessary as the tsunami floods are limited to the coastlines of Shimizu and Suruga.

During the course of the day there are several times where population shifts its location from home to workplace and the opposite. These times can be defined as transit hour times, where the people of the city move massively. The time with the highest movement of people is the early morning hours when everyone is going to work, from 7 till 10 am. However, this is not the only time that people are on the move. As mentioned in earlier chapters there is a discreet movement during lunch time, when many people either return home or move to another location for lunch. Also, the evening rush hour is less extensive in quantity but takes more hours to complete, slowly starting from about 16 pm in the afternoon and finishing at 21 pm. During these transit hours where there is a lot of movement, vertical evacuation greatly depends on the location that people find themselves, and the severity of the tsunami. For example, if there is a severe tsunami happening and you are in transit in the early morning rush hour, then movement towards the CBD is necessary, but the building that the vertical evacuation takes place can be either a workplace or a residence, however, residences a more likely to be less congested. For the weaker scenarios, people only need to worry about vertically evacuating during rush hours if they are close to the coastline of the city. For example, at 18 pm in the afternoon in the area of Shimizu, a person who is in transit walking home, will need to locate the closest workplace to vertically evacuate, although residences are not completely full at that time either, workplaces tend to be more empty in the late afternoon hours.

Figure 5-3 Clustering of potential vertical evacuation sites per tsunami scenario

Figure 5-4 Vertical evacuation movements per tsunami severity, time of the day and location during the tsunami

Chapter 6 Conclusions

The city of Shizuoka faces a tsunami hazard due to its proximity to the Nankai Trough that can potentially lead to different tsunamis that can with a maximum run up of 34m. Such a tsunami could prove to be catastrophic not only for the city itself, but it would affect Japan in general, as Shizuoka is an important node in the country's transportation networks. Under these circumstances, it became the purpose of this research to determine where and when people can safely evacuate vertically, during different tsunami severities.

There is ample literature describing a 100-200 year return interval of tsunamis in the area ranging from 5m to 10m and up to 20m and 34m run up heights. Tsunami hazard mapping allowed not only to visualize the above four scenarios but to estimate the amounts of buildings that will be affected by the tsunami waters in each case. The weak 5m and 10m scenarios affect the city locally in the coastlines of Suruga and Shimizu, but the severe scenarios lead to extensive flooding that spans to the greater extent of the city in whole. The variable tsunami hazard mapping that was undertaken ensured viable results for different severity cases.

Due to the variability of the tsunami scenarios, buildings were found to become flooded in different ways depending on the tsunami severity and the building height. The inundation ratio analysis showed that different buildings can or cannot be used in different scenarios due extensive flooding, often times leading in the complete loss of the building. This loss of building volume due to the flood proved to be an important index as it showed the amount of volume that was left that could be used for vertical evacuation. The results of this analysis showed that in the weak scenarios there is ample volume for vertical evacuation within the flood zone itself, but the available volume is greatly limited spatially to the area of the CBD in the severe scenarios. This has serious implications to vertical evacuation in severe scenarios as it requires great amounts of movement toward the area of the CBD from most of the areas of the city.

This volume availability was proven to be variable itself, not just spatially but also during different times of the day. The application of a 24 hour building population estimation model allowed

to estimate how the population in the buildings of the whole of Shizuoka City shifts during different times of the day. It became apparent that residencies are emptier in the morning hours, but not completely empty, and that buildings that work at are almost completely empty in the evening and late night hours. More importantly, it is evident that there are numerous shifts in building population over the day, as people move towards work or school, towards home, or returning home for lunch and back to work. The population movements over the course of a day led to the identification of time periods of the day where the population is found in different states: a) nighttime, where the majority of the population is at home spread all over the city except for the CBD which is mostly empty, b) daytime, where a great part of the population has concentrated in the CBD area for work, and a small part stayed at home, leaving the residential buildings in the rest of the city occupied with minimal numbers of people, and c) the transit hours, during which people are out of buildings moving towards work or returning home, either walking or using transportation means.

Based on these findings it was clear that vertical evacuation had a spatiotemporal nature, and in order for it to be successful different buildings should be used at different times, and at different tsunami severities. Vertical evacuation criteria were introduced in order to identify buildings that could be used as potential vertical evacuation sites in case of a tsunami event. The criteria considered the extent that a building becomes flooded, and are mores strict in the weaker scenarios and less strict in the severe ones. Moreover, the criteria assigned a certain amount of volume per person in the building, allowing to estimate the amounts of extra persons that can be accepted in the remaining building volume for vertical evacuation. This analysis clearly showed that in the building stock currently available in the city of Shizuoka, the majority of the population can be vertically evacuated in the volume left after the occurrence of each of the four tsunamis. However, the spatial distribution of the available volume varies per tsunami scenario showing discreet differences between the severe and weak cases. In the case of the latter, vertical evacuation can be done at the full extent of the tsunami flood zones and with multiple options, during all times of the day. While vertical evacuation is possible volume wise, in the severe scenarios, it is limited spatially only in the area of the CBD

requiring extensive movement from anywhere in the city towards the CBD, in order vertically evacuate. The available volume for vertical evacuation, is also variable based on the time and building use. In the morning hours, workplaces are expected to be congested with people being at their work, while in the evening and late hours residences were found to be congested, leaving buildings that are workplaces empty.

This study has used methods from different fields of geography and combined them in an original approach, presenting evidence that vertical evacuation while possible, depends on different variables and is spatiotemporal in nature. While it is possible to find vertical evacuation sites during different times of the day and in all severities of tsunami scenarios, the spatial distribution of these sites is not always ample and plentiful, and careful planning and further analyses should be conducted in order to explore the ways that the vertical evacuation should be done in the locations that this study has identified. The findings of this research contradict the approach of the vertical evacuation plan of Shizuoka City, which considers a single tsunami scenario and a "tall building" approach to its suggested vertical evacuation sites. As such, it is recommended that the method and results of this research are considered by the local governments in order to deduce an updated vertical evacuation plan, especially for the cases of the severe tsunami scenarios. The results of this research uniquely provide multiple vertical evacuation options, that do not require the construction of additional buildings or facilities, requiring virtually no monetary cost, just an implementation plan. The finalized version of such a vertical evacuation plan should include the locations, paths and times of availability of vertical evacuation sites, in different tsunami scenarios. Moreover, it should include the policies required of allowing the buildings to be used by everyone, at different times of the day during a tsunami emergency event.

This study has contributed to scientific knowledge by providing an understanding of the spatiotemporal nature of tsunami vertical evacuation through the case study of a tsunami prone city. The methods utilized and combined originate in fields of Geography that are otherwise considered to be of remote relationship, into a tsunami vertical evacuation site identification method that is modular

and adaptable to different datasets, applicable in any tsunami prone urban location that meets or exceeds its data requirements.

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“Patriotism, weapons, armies, navies, all that is a sign that we're not civilized yet. Kids will ask their parents, "Didn't you see the necessity of the machines? Dad, couldn't you see that war was inevitable when you produce scarcity? Isn't it obvious?" Of course, the kid will understand, that you were pinheads, raised merely to serve the established institutions. We're such an abominable, sick society, that we won't make the history books, they'll just say that large nations took land from smaller nations, used force and violence. You'll get history talked about as corrupt behavior all the way along, until the beginning of the civilized world, that's when all the nations worked together. World unification, working toward for common good for all human beings, and without anyone being subservient to anyone else. Without social stratification, whether it is technical elitism, or any other kind of elitism, eradicated from the face of the earth.” - Jacque Fresco

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Appendix

24h building population estimation transitions in the CBD of Shizuoka over a 20m tsunami scenario.

6am building population estimation

7am building population estimation

8am building population estimation

9am building population estimation

10am building population estimation

11am building population estimation

12pm building population estimation

13pm building population estimation

14pm building population estimation

15pm building population estimation

16pm building population estimation

17pm building population estimation

18pm building population estimation

19pm building population estimation

20pm building population estimation

21pm building population estimation